A Tool for Rating the Resilience of Critical Infrastructures in Extreme Fires

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Abstract

This report provides the results of the study conducted by NRC on developing a tool and testing procedure for rating resilience of critical infrastructures to extreme fire. Resilience of critical infrastructures to extreme fire is also referred in this report as extreme fire resistance or fire endurance. The current available test procedures for testing structures in extreme fires or hydrocarbon fires were reviewed. The available guidelines and standards were developed mainly for application in oil refinery and chemical industry facilities. The only available standard in North America that addresses the transportation infrastructure is the NFPA 502 standard. However, even this standard has only a procedure for testing of tunnel linings in extreme fire to some extent. No standard, guidelines or document was found for assessing bridges or important buildings to extreme fire. Through this project and based on the review of information available, a draft of a new testing procedure was prepared for resilience assessment of critical infrastructures to extreme fire. An Advisory Board with members from the regulatory bodies and related experts was formed to review the draft document and provide recommendations toward developing a practical testing procedure. The testing procedure was reviewed by the Advisory Board members and discussed through two meetings. The outcome was presented in this report and recommended as guidelines for extreme fire resistance of critical infrastructures. Finally, to demonstrate the applicability of the guidelines, a commissioning test was carried out successfully using the NRC column furnace test facility based on the developed guidelines.

This report presents the outcomes of the review study, the developed testing procedure, and the results of the demonstrated test.

Résumé

Le présent rapport fournit les résultats de l'étude dirigée par le CNRC sur la mise au point d'un outil et d'un protocole d'essai permettant de classifier la résilience des infrastructures essentielles (IE) en conditions d'incendie extrêmes. Dans le présent rapport, la résilience en conditions d'incendie extrêmes est également désignée résistance en conditions d'incendie extrêmes ou simplement résistance au feu. Les protocoles d'essai qui sont actuellement disponibles pour mettre à l'essai les structures dans des conditions d'incendie extrêmes ou de feux de nappes d'hydrocarbure ont été examinées. Les lignes directrices et les normes existantes ont été créées essentiellement pour fin d'application dans les raffineries de pétrole et les installations de l'industrie chimique. La seule norme disponible en Amérique du Nord qui vise l'infrastructure de transport est la norme NFPA 502. Or, même cette norme ne comporte qu'un protocole pour mettre à l'essai les revêtements des tunnels en conditions d'incendie extrêmes et dans une certaine mesure seulement. Il n'existe aucune norme, aucune ligne directrice ni aucun autre type de document aux fins d'évaluation des ponts ou des bâtiments importants en conditions d'incendie extrêmes. Par le biais du présent projet et en nous fondant sur l'examen de l'information disponible, l'ébauche d'un nouveau protocole d'essai pour l'évaluation de la résilience des IE en conditions d'incendie extrêmes a été préparée. Un conseil consultatif (CC) dont les membres sont des représentants d'organismes de réglementation et des experts rattachés au domaine a été mis sur pied pour examiner le document préliminaire (l'ébauche) et fournir des recommandations en vue de l'élaboration d'un protocole d'essai pratique. Le protocole d'essai a été examiné par les membres du CC et a fait l'objet de discussions lors de deux réunions. Les conclusions de ces réunions sont exposées dans le présent rapport et recommandées comme lignes directrices en vue de l'amélioration de la résistance en conditions d'incendie extrêmes des IE.

Enfin, dans le but de démontrer l'applicabilité des lignes directrices, et en se fondant sur celles-ci, un essai de mise en marché en utilisant avec succès le four d'essais sur poteaux de l'installation d'essais du CNRC a été réalisé.

Le présent rapport expose les conclusions de l'étude analytique, le protocole d'essai mis au point et les résultats de l'essai démontré.

Executive summary

Background:

This project developed a generic approach that could be used for the emerging risk assessment and mitigation of extreme fire threats to the Canadian critical infrastructures (CIs). This study developed guidelines for fire resistance assessment/rating of physical critical infrastructures that include bridges, tunnels, and critical buildings (e.g. government buildings across the country and Canadian embassies). Whether for the design of a new critical infrastructure or protecting and retrofitting an existing one, reliable evaluation/testing guidelines, as well as a testing facility are of vital need to investigate the effectiveness of different technologies and solutions. Currently, there are few fire resistance rating standards; however, they have shortcomings in application and cannot be used for assessing the fire resistance rating of critical infrastructures under extreme fires. The outcome of the proposed project provides the CIs community with practical guidelines to perform such fire resistance rating tests for CIs. NRC has been upgrading its fire testing facilities to be able to perform resilience evaluation/rating of critical infrastructures to extreme fires. The upgraded facility and testing guidelines will enable the Canadian safety and security stakeholders to perform more accurate vulnerability assessment and develop more reliable and effective protection systems for critical infrastructures against the emerging risk of extreme fires. This report provides the results of the commissioning tests using these facilities based on the guidelines developed in this project.

The extreme fire resistance test procedure was developed based mainly on literature reviews and studies of available fire resistance tests, with comparable fire severity and structural systems. An Advisory Board (AB) with members, including experts from relevant fields and regulatory bodies was formed. The main role of the Advisory Board was to review the test procedures and provide recommendations for application of the test procedure for test of critical infrastructure to extreme fires. Members of the AB were experts from transportation sectors, fire services, testing laboratories, fire consulting community and regulatory bodies in safety and security. This report includes the developed testing procedure.

A test was performed to demonstrate application of the test method using the NRC column test facility. The test results are also provided in this report.

Results: The main outcomes of this project include:

1) Main available extreme fire test guidelines were reviewed and listed.

2) A test procedure for extreme fire assessment of critical infrastructures including bridges, tunnels and important buildings was developed.

3) A test was successfully performed to demonstrate the applicability of the developed extreme fire test procedure.

Significance: The testing guidelines developed in this project will provide a tool for critical infrastructure communities to undertake vulnerability assessments of critical infrastructures to extreme fire and to develop the required protection solutions. This tool can be used by the critical infrastructures stakeholders to help them in decision making to efficiently enhance structural integrity, safety and security of critical physical infrastructures against extreme fires.

Future plans: Using the developed testing procedure, NRC will assist transportation sector, Department of Foreign affairs (for Canadian embassies), and other OGDs, (for critical government buildings and properties) to develop solutions for resilience enhancement of critical infrastructures to extreme fires. Furthermore, the outcome will provide a tool for NRC to help the Canadian industry to develop extreme fire protection materials and technologies for critical infrastructures.

Future plan includes R&D:

- To develop and test materials and technologies for protection of critical infrastructures (CIs) against extreme fires.

- To develop methods and technologies to assess and mitigate risk of extreme fires to CIs and to enhance their resilience to such threats.

Sommaire

Contexte : On a élaboré dans le cadre du présent projet une approche générique qui pourrait être utilisée aux fins de l'évaluation du risque émergent et de l'atténuation des menaces d'incendies extrêmes pour les infrastructures essentielles (IE) canadiennes. Cette étude a engendré des lignes directrices pour l'évaluation / le classement de la résistance au feu des IE physiques comprenant les ponts, les tunnels, les bâtiments essentiels, soit les immeubles gouvernementaux à l'intérieur du pays et les ambassades canadiennes. Que ce soit pour concevoir une nouvelle IE ou pour protéger et modifier en rattrapage une IE existante, des lignes directrices d'évaluation / de mise à l'essai rigoureuses, de même que l'accès à une installation de mise à l'essai fiable sont d'une nécessité vitale pour permettre d'investiguer l'efficacité de différentes technologies et solutions. À l'heure actuelle, il n'existe que peu de normes sur le classement de la résistance au feu; par ailleurs, elles comportent des lacunes dans leur application et ne peuvent pas être utilisées pour évaluer le classement de la résistance au feu des IE en conditions d'incendie extrêmes. Le projet proposé a pour résultat de fournir aux réseaux des IE des lignes directrices pratiques pour réaliser de tels essais de classement de la résistance au feu pour les IE. Le CNRC a amélioré son installation de recherche en incendie afin d'être à même de réaliser l'évaluation de la résilience / du classement des IE en conditions d'incendie extrêmes. L'installation améliorée et les lignes directrices de mise à l'essai permettront aux intervenants en matière de sécurité et de sûreté au Canada de réaliser des évaluations plus précises de la vulnérabilité des installations et de développer des systèmes plus fiables et efficaces pour protéger les IE contre le risque émergeant de conditions d'incendie extrêmes. Le présent rapport fournit les résultats des essais de mise en marché au moyen de ces installations, fondées sur les lignes directrices élaborées dans le cadre de ce projet.

Le protocole d'essai de résistance en conditions d'incendie extrêmes a été élaboré à partir essentiellement des analyses documentaires et des études des méthodes d'essai de résistance au feu existantes, avec indice de gravité d'incendie et systèmes structuraux comparables. Un conseil consultatif (CC), ayant comme membres des représentants d'organismes de réglementation et des experts rattachés, a été mis sur pied, dont le principal rôle était d'examiner les protocoles d'essai et de fournir des recommandations pour l'application du protocole d'essai retenu pour les essais des IE en conditions d'incendie extrêmes. Les membres du CC étaient des experts du secteur des transports, des services d'incendie, des laboratoires d'essai, du domaine de la consultation en sécurité incendie et d'organismes de réglementation en sécurité et en sûreté. Le présent rapport contient le protocole d'essai élaboré.

Un essai a été réalisé dans le but de démontrer l'application de la méthode d'essai, au moyen de l'installation d'essais sur poteaux du CNRC. Les résultats d'essais sont également fournis dans le présent rapport.

Résultats : Les principaux résultats de ce projet sont les suivants :

1) Les principales lignes directrices existantes en matière d'essais en conditions d'incendie extrêmes ont été examinées et répertoriées.

2) Un protocole d'essai pour fin d'évaluation des incendies extrêmes en ce qui a trait aux IE tels que ponts, tunnels et bâtiments importants a été élaboré.

3) Un essai a été réalisé avec succès dans le but de démontrer l'applicabilité du protocole en conditions d'incendie extrêmes élaboré.

Pertinence : Les grilles d'essai mises au point dans le cadre du présent projet procureront un outil qui permettra aux réseaux des IE d'effectuer des évaluations de la vulnérabilité de celles-ci en conditions d'incendie extrêmes et d'élaborer les solutions requises en matière de protection. Cet outil peut être utilisé par les intervenants des IE comme auxiliaire dans les prises de décision, en vue d'améliorer avec efficacité l'intégrité structurale, la sécurité et la sûreté des infrastructures physiques essentielles face aux conditions d'incendie extrêmes.

Prospective : Grâce au protocole d'essai élaboré, le CNRC pourra aider le secteur des transports, les affaires extérieures (ambassades) et d'autres ministères (immeubles et autres biens gouvernementaux essentiels) à mettre au point des solutions d'amélioration de la résilience des IE en conditions d'incendie extrêmes. En outre, les résultats procureront un outil qui permettra au CNRC d'aider l'industrie canadienne à développer des matériaux et des technologies de protection contre les incendies extrêmes pour les IE.

La prospective comprend de la recherche et développement pour :

- Le développement et la mise à l'essai des matériaux et des technologies pour la protection des IE contre les conditions d'incendie extrêmes.

- Le développement de méthodes et de technologies permettant d'évaluer et d'atténuer les risques de conditions d'incendie extrêmes pour les IE et d'améliorer leur résilience face à de telles menaces.

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1 Introduction

Recent studies on the response of Canadian transportation infrastructures to extreme fires [1, 2] indicated that critical infrastructures such as bridges are not designed for extreme fires and are vulnerable to such threats, which could be either deliberate or accidental. Studies on the recent bridge fires reported more than 500 fatal crash events on bridges in the last 14 years across the U.S. and Canada [1, 3]. These incidents resulted in millions of dollars of loss due to the direct cost of the bridge damage and repair and indirect economic impact on the community as a result of the delays in the bridge recovery after the incidents.

Despite this large number of critical infrastructure fire incidents, the only current document in North America that reflects some requirements for protection of transportation infrastructures to fire is NFPA 502 "Standard for Road Tunnels, Bridges, and Other Limited Access Highways". NFPA 502 provides designers and regulators with guidelines for the construction, operation, maintenance, and fire protection of tunnels and bridges to mitigate hazards, maintain structural integrity, and protect lives. Although the scope of NFPA 502 is tunnels and bridges, most of the developed information is for the design and protection of tunnel linings, to some extent. There is currently no guideline or test procedure for assessment of the resiliency of the critical infrastructures, such as bridges and critical buildings to extreme fires.

Therefore, the scope of this study was primarily set on developing a testing tool or guideline for resilience assessment of critical infrastructures, inclusive of bridges, tunnels and important buildings, e.g. embassies and government buildings, to extreme fires. This tool will help the community of practice to develop solutions for the resilience enhancement of critical infrastructures to deliberate or accidental threats from extreme fires.

2 Purpose

The main objectives of this project were:

- To develop test procedures for extreme fire resistance assessment of critical infrastructures, which in the context of this study are primarily inclusive of roadway tunnels and bridges, subway/railway tunnels and bridges and high profile buildings that may have either local, regional or national socio-economic, geographic, strategic and/or political significance.

- To demonstrate an extreme fire based on the developed test procedure.

3 Methodology

The main methodology employed for the implementation of this study includes technical reviews and experimental demonstration. This chapter describes the main outcome of this project which includes the test procedure, the discussions by the Advisory Board members and the results of the demonstration test. The results for the literature review and a numerical method are provided in the appendixes.

3.1 Test Methods for Rating the Resistance of Critical Infrastructure Structural Members in Extreme Fires

3.1.1 Scope

3.1.1.1 Extreme fires are, in the context of this document, hydrocarbon fires, or pool fires, that burn above a pool of vaporizing hydrocarbon petroleum fuel and characterized with a rapid heat rise. They are either outdoor free-burning fires, e.g. bridge fires, or confined fires, e.g. in tunnels.

3.1.1.2 This test method is applicable to typical structural elements including columns, beams, slabs and walls of critical infrastructures with or without passive fire protection insulations.

3.1.1.3 The test method is to evaluate the length of time that the types of structural elements specified in 3.1.1.2 will retain their structural stability and integrity during a predetermined extreme fire exposure.

3.1.1.4 This test method does not purport to address all the risks associated with safety or property protection of the specified critical infrastructures. The test determines fire resistance of the structural elements to extreme heat exposure under controlled conditions, and does not by itself incorporate all factors required for fire hazard or fire risk assessment of critical the infrastructure elements under actual extreme fire conditions.

3.1.2 Assumptions

3.1.2.1 The test method is intended to determine fire resistance rating under extreme exposure of the specified structural elements in 3.1.1.1 and 3.1.1.2. The fire resistance rating is the duration for which the structural elements retain the structural stability and integrity during a predetermined extreme fire exposure.

3.1.2.2 The specified structural elements include reinforced concrete, steel, or composite structural elements of tunnels (mainly concrete linings of road tunnels), bridges (mainly concrete, steel or composite decks or columns of overpasses), and buildings (mainly steel, concrete or composite floors, columns and walls of typical multi-storey office building structures).

3.1.2.3 The extreme fires are hydrocarbon fires that burn above a pool of vaporizing hydrocarbon petroleum fuel (mainly gasoline tanker truck fires) and have a rapid heat rise.

3.1.2.4 The test exposes a specimen to a standard controlled fire to achieve specified temperatures throughout a specified time period.

3.1.3 Constraints

3.1.3.1 The test method does not provide the following:

- Evaluation of active fire protection methods or systems or other techniques not appropriate for evaluation by this method.

- Information as to performance of specimens constructed with components or lengths other than those tested.

- Evaluation of the degree by which the specimen contributes to the fire hazard by generation of smoke, toxic gases, or other products of combustion.

- Measurement of the degree of control or limitation of the passage of smoke or products of combustion through the specimen.

- Simulation of the fire behavior of joints between element or segment connections.

- Measurement of flame spread over the surface of specimen.

- Evaluation of structural elements of railway tunnels and bridges, subway tunnels, with a different level of fire severity than that specified in Section 3.1.2, Assumptions.

- Evaluation of structural elements with fire exposure from above. Although a worst case scenario for these elements would be to test them with fire exposure from underneath, such as in the case of fire under a bridge overpass.

- The test method does not apply to scenarios of fuel explosions, e.g. boiling liquid expanding vapor explosion or fuel air explosion, but rather typical fuel tanker fires and deflagrations with ignorable pressure effects on CIs.

- The test method is limited to critical infrastructures with comparable extreme fire loads and structural systems as those specified in the assumptions.

3.1.4 Control of Fire Tests

3.1.4.1 Extreme fire time-temperature curves that are considered applicable to this study for different critical infrastructures include ASTM 1529 and Rijkswaterstaat (RWS) time-temperature curves. A description of these time-temperature curves are provided in Appendix A

3.1.4.2 Furnace Temperature

- Applying ASTM E1529 time-temperature curve:
    - Enclosed furnace should be used for the tests.
    - The average furnace temperature shall be at least 1500°F (815°C) after the first 3 min of the test and shall be between 1850°F (1010°C) and 2150°F (1180°C) at all times after the first 5 min of the test.

- A minimum heat flux of 150 kW/m^2 needs to be achieved during the tests.

  Note 1: when using furnaces for the tests, controlling maximum heat flux is not easily feasible. Therefore, only minimum heat flux is suggested to be monitored, which is on the conservative side.

  Note 2: UL1709 is similar to ASTM E1529 in various aspects. For UL1709 temperature limits are 1093±56 ^{o}C. Practically, when producing an extreme fire using an enclosed furnace, meeting the temperature limits for both standards is easily achievable. The demonstration test in 3.3 showed that by achieving the average temperature, the minimum heat flux was more than 188 kW/m^2, satisfying both UL1709 (188 kW/m^2) and ASTM E1529 (150 kW/m^2) for the required minimum heat flux.

- Applying RWS time-temperature curve:

  - The average furnace temperature obtained from the readings of control thermocouples shall follow the control time-temperature curves provided in section 3.1.4.1 for RWS, within the following percentage deviation. The percentage deviation dc, in the area under the average time-temperature curve recorded by the specified furnace thermocouples from the area under the prescribed time-temperature curve shall be within:

    dc 15% for $5< t <10$

    dc 10% for $10 < t < 30$

    dc 5% for $30< t$

    where $dc= (A - A_S)/A_S \times 100$

    in which: dc is the percentage deviation, A is the area under the actual furnace temperature-time curve in ^{o}C, A is the area under the prescribed temperature-time curve in ^{o}C and t is the time in minutes.

3.1.4.3 Furnace thermocouple specifications

- Applying ASTM E1529 time-temperature curve

  - As specified by ASTM 1529 [5] or equivalent thermocouples, e.g. Inconel sheathed, Type K.

- Applying RWS time-temperature curve

  - As specified by the RWS [9] or equivalent thermocouples, e.g. high temperature sheathed type-K.

3.1.4.4 Read the temperature at intervals not exceeding 1 min

3.1.5 Test Facility

3.1.5.1 For full-scale tests

- The wall, floor and column furnace facilities required for the test method shall have the same configuration and design as those of the Test Methods ASTM E119 [7].

3.1.5.2 For intermediate-scale tests

- The intermediate-scale furnace test facilities are used for spalling test and passive fire protection test of tunnel linings. They shall accommodate specimen configurations with a minimum surface area of 1.44 m^2 and minimum side of 1.00 m, e.g. 1.20 m×1.20 m or 1.00 m×1.44 m

3.1.6 Calibration of Furnace Test Facilities

3.1.6.1 The full-scale furnace test facilities shall be calibrated based on the procedure provided by the applicable standard, ASTM E1529 (UL1709) or RWS.

3.1.6.2 The Intermediate–scale furnace facilities, until specifications are defined by the standard bodies, calibrations shall be performed according to a related available standard.

3.1.7 Test Methods

3.1.7.1 Column Tests

- Loaded Specimens
    - Columns shall be tested according to ASTM E1529 in a vertical orientation. The exposed length of the column shall be not less than 9 ft (2.74 m). All sides of the columns shall be exposed to the fire. The support or end conditions shall be satisfied according to methods of practice in the field.
    - During the fire test, the column shall be subjected to a superimposed load that shall be determined as the maximum load condition allowed under nationally recognized structural design criteria. Exception is applied when limited design criteria are specified with a corresponding reduced load.
    - Extreme fire resistance of the column specimen is determined as the length of time that the column retains the superimposed load during the test fire section 3.1.4 until it fails. The failure criteria are:
        - Stability Criterion: when the column could not sustain any further the superimposed load.

- Integrity Criteria (for concrete elements if property protection is required): the integrity criteria are described in Appendix D.

- For unloaded column specimens follow ASTM E1529.

3.1.7.2 Beam and Slab Tests

- Loaded Specimens

  - Beam/slab shall be tested in a horizontal orientation. The exposed length/area of the assembly shall not be less than 13 ft (3.9 m) for beams and 13ft×16ft (3.9 m x 4.8 m) for slabs. The assembly shall be exposed to the fire from underneath, for beams from three sides, except the top side.

  - During the fire test, the beam/slab shall be subjected to a superimposed load that shall be determined as the maximum load condition allowed under nationally recognized structural design criteria. Exception is applied when limited design criteria are specified with a corresponding reduced load.

  - The ends of the beam/slab shall be simply supported and they shall not be restrained against thermal expansion in the support direction, except tunnel linings when membrane action is required.

  - Extreme fire resistance of the beam/slab specimen is determined as the length of time that the beam/slab retains the superimposed load during the test fire section 4 until it fails. The failure criteria are:

    - Bridges and tunnels (load bearing elements):

      - Stability Criterion: when the beam/slab could not sustain any further the superimposed load.

      - Integrity Criteria (for concrete elements if property protection is required): the integrity criteria are described in Appendix D.

    - Buildings:

      - Failure criteria requited by the ASTM E119* shall be employed.

      - Integrity Criteria (for concrete elements if property protection is required): the integrity criteria are described in Appendix D.

- For unloaded slab specimens, applicable for buildings, follow ASTM E119*.

* Note that E1529 does not address the floor and slab tests for typical buildings, until such information available, E119 referenced here.

3.1.7.3 Unloaded Tunnel Ceiling Lining Test

- To test spalling and passive fire protection tunnel ceiling lining specimens, the test instructions and failure criteria provided by Efectis 2008 could be employed.

3.1.7.4 Wall Tests

- Load bearing walls (buildings, and for bridges and tunnels when perpendicular load is ignorable):
  - Walls shall be tested according to ASTM E119* in a vertical orientation. The wall specimen shall have a fire-exposed surface of not less than 9 m^2, with neither dimension less than 2.7 m. The test specimen shall not be restrained on its vertical edges.
  - During the fire test, the wall shall be subjected to a superimposed load that shall be determined as the maximum load condition allowed under nationally recognized structural design criteria. Exception is applied when limited design criteria are specified with a corresponding reduced load.
  - The wall shall be installed as simple pin-pin connection conditions at the top and bottom ends.
  - Extreme fire resistance of the wall specimen is determined as the length of time that the wall retains the superimposed load during the test fire section 4 until it fails. The failure criteria are:
    - Bridges and tunnels
      - Stability Criterion: when the wall could not sustain any further the superimposed load.
      - Integrity Criteria (for concrete elements if property protection is required): the integrity criteria are described in Appendix D.
    - Buildings:
      - Failure criteria required by the ASTM E119* shall be employed
      - Integrity Criteria (for concrete elements if property protection is required): the integrity criteria are described in Appendix D.
- For unloaded wall specimens, applicable for buildings, follow ASTM E119*.

* Note that E1529 does not address the structural walls for typical buildings, until such information available, E119 referenced here.

3.1.7.5 Non load bearing tunnel Wall Lining Test

- To test spalling and passive fire protection of tunnel wall lining specimens, the test instructions and failure criteria provided by Efectis 2008 could be employed.

3.1.8 Conditioning Specimens

- For specimens where conditioning environments, e.g. weathering exposure, are required, they should be conditioned as applicable based on the appropriate standards, e.g. for tunnels, requirements are provided by NFPA 502 and for bridges, UL1709 could be employed.

3.1.9 Related Standards and Guidelines

- ASTM E 176 Terminology of Fire Standards
- ASTM E1529 Standard Test Methods for Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies
- ASTM E119 Test Methods for Fire Tests of Building Construction and Materials
- UL 1709 Rapid Rise Fire Tests of Protection Materials for Structural Steel
- Efectis Nederland Report – 2008-Efectis-R0695, Fire Testing Procedure for Concrete Tunnel Linings

3.2 Review of the Test Procedure

An Advisory Board (AB) was formed with members from extreme fire experts, fire service, safety and security and regulatory bodies. The primary goal of the Advisory Board was to review and provide comment/input on the developed process/guideline for testing of critical infrastructures to extreme fires. List of the advisory board members are provided in Appendix C as part of the project team. Two advisory board meetings were held during the course of this project. This section provides the highlights and recommendations extended by the Advisory Board members during the implementation of this study and the two AB meetings. Details of the discussions, minutes of the AB meeting are provided in Appendix A.

3.2.1 Advisory Board Meeting 1

The first meeting was held on Wednesday, 18 December 2013, 1:00pm – 3:00pm (Eastern Time) at the National Research Council Canada. The main purpose of this meeting was to review the proposed time-temperature curves in the test procedure for different critical infrastructures.

- The outcome of this first meeting can be summarized as follows:
  - A presentation titled "Test Methods of rating the resistance of critical infrastructure structural members in extreme fires" was delivered.
  - This project will help develop a test procedure that will enhance resilience of critical infrastructures and particularly the transportation infrastructures against extreme fires threats, mainly the security aspect when a gasoline tanker would be used as a weapon to attack a critical infrastructure.
  - Information on the large scale pool fire tests carried out by Sandia National Laboratories shows heat release rate of extreme fire could be over 500 MW.
  - The fire scenarios, fire severity, under the bridge and on the bridge would be different. However, fire underneath, in the proposed test procedure, is a worst case scenario compared to that on the bridge.
  - Type of fuel could result in different fire severity. Gasoline, or any fuel with equivalent thermal properties that result in similar fire load, is considered applicable for the proposed test procedure.

    Heat flux is suggested to be measured and monitored during the test. Continuous heat flux measurements are recommended to support the risk assessments.
  - Post fire actions are important. Data are needed to understand how many fires occurred on the bridges.
  - Data on the number of fire incidents on critical infrastructures are needed.
  - Fire threat, risk, and tolerance of loss will be different depending on the specific structure and the potential fire scenarios. How we have been dealing with tunnels could also be applicable in the bridges.
  - RWS could be good for rail tunnels but not for subway tunnels as fire load is different.
  - RWS would be considered applicable for cargo/freight rail tunnels.

3.2.2 Advisory Board Meeting 2

The second meeting was held on Wednesday, 29 January 2014, 1:00pm – 3:00pm (Eastern Time) at the National Research Council Canada. The main purpose of this meeting was to review the remaining sections of the test procedure.

- A summary of the meeting outcome includes:
  - Heat flux meters need to be added to the test procedure to measure heat flux during the tests. Note that in some scenarios, such as nuclear plants test procedure, specific heat flux devices are required.
  - The furnace test is suggested to be controlled with temperature but to monitor heat flux during the test.
  - The size of the specimen could affect the heat flux.
  - Future tests are recommended to estimate the heat flux and temperature for a bridge using a real tanker fuel fire scenario.
  - RWS does not require measuring heat flux because of the furnace condition. The radiation in the furnace would satisfy the requirement for heat flux. This would be applicable also for UL1709 and ASTM E1529, based on the recent tests performed by NRC [2].
  - In RWS, the deviations are checked for both temperatures and area under the temperature time curve.
  - Some challenges would be in achieving RWS curve for large unprotected concrete samples due to the large heat sink to concrete.
  - K-type thermocouples have been used in Europe for RWS tests, rather than the specified B-type. There are also Type N thermocouples for high temperatures.
  - When spalling occurs that could be a failure criterion.
  - The decay phase of fire also needs to be performed by the furnace to have more realistic performance and spalling effects.
  - Fire service may be a concern in the practice of cooling the concrete structure exposed to heat by water spray if it could cause more spalling. However, spraying water on a hot concrete surface would result in reducing temperature, which could reduce the spalling effect. No test is available to confirm this assumption.
  - Spalling needs to be checked after 24 hours, since during the cooling phase spalling could continue.
  - The purpose of RWS is that if the specimen passes the test, after any fire, it would need only minor repair or change of the fire protection.
  - Compression tests for heated samples could provide valuable information on residual strength.
  - Explosive spalling could be a failure criterion as well.

3.3 Demonstration Test

A demonstration test was performed to show that the test procedure is feasible. The test was done to produce an extreme fire based on ASTM E1529 (UL1709). To ensure that both temperatures and heat flux are satisfied, the calibration test specified by these two standards was commissioned. Both standards have almost the same calibration test procedure. This calibration test would be applicable for test of loaded or unloaded bridge and building column elements.

3.3.1 NRC Fire Lab

NRC has three full-scale furnace testing facilities and one intermediate-scale testing facility; for testing walls, Fig. 1, for testing floors/beams, Fig. 2, and for testing columns , Fig. 3, and one smaller scale furnace for testing intermediate-scale specimens, Fig. 4. Recently, these facilities have been upgraded to become capable of producing extreme fire tests, e.g. tunnel fires, and bridge fires. The column furnace was selected for this study for the demonstration test in this project, as an example.

Figure 1. NRC full-scale wall furnace for testing loaded and non-loaded walls

Figure 2. NRC full-scale column furnace for testing loaded columns

Figure 3. NRC full-scale column furnace for testing loaded columns

Figure 4. NRC intermediate-scale furnace for testing walls/floors/slabs

3.3.2 Fire Exposure

For calibration, 3.1.6.1 requires to follow the applicable standards. Since for bridges and buildings ASTM E1529 and UL1709 are the applicable standards, the calibration test was carried out based on the specifications provided by these two standards. The attempt was to try to meet the requirements of both UL1709 and ASTM E1529. Figure 5 shows the time temperature curve used to control the demonstration test. To meet 3.1.4.2 (or ASTM E1529), the temperatures after 5 minutes should be kept between 1010^{o}C and 1180 ^{o}C. To meet UL 1709, temperatures after 5 minutes should be kept 1093±56 ^{o}C.

3.1.4.2 (or ASTM E1529) also requires that the temperature should reach 815 ^{o}C within the first 3 minutes, which is not the requirement of UL1709.

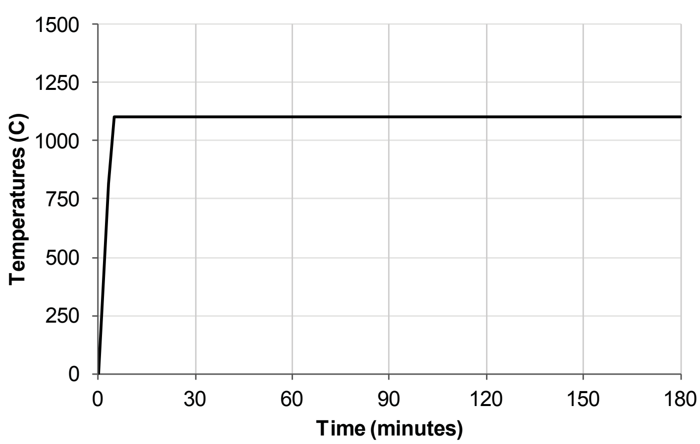

Figure 5. Time-temperature curve for test of bridges and buildings in extreme fire.

For calibration, heat flux also needs to be monitored and checked. 3.1.4.2 requires the test to provide a minimum of 150 kW/m^2 heat flux. ASTM E1529 requires an average total cold wall heat flux on all exposed surfaces of the test specimen of 158 $kW/m^2 \pm 8$ kW/m^2 within the first 5 min of test exposure and be maintained for the duration of the test. On the other hand, UL1709 requires development of a heat flux of $204 \pm 16 kW/m^2$ within the first 5 minutes of the test. However, controlling both minimum and maximum heat flux is not easily feasible when using furnaces. Hence, only the required minimum heat flux is suggested to be employed during the test, which is on the conservative side. For 3.1.4.2 (ASTM E1529), the required minimum heat flux is $150kW/m^2$ and for UL1709 it is 188 kW/m^2.

3.3.3 Test Specimen

Calibration sample sizes and specifications are mostly the same in ASTM E1529 and UL1709. The test sample was built to meet the UL1709 and ASTM E1529. Figure 6 shows the dimensions for the test samples required by the standards. Figures 7 and 8 show the specimen that was built according to the specifications and installed in the column furnace.

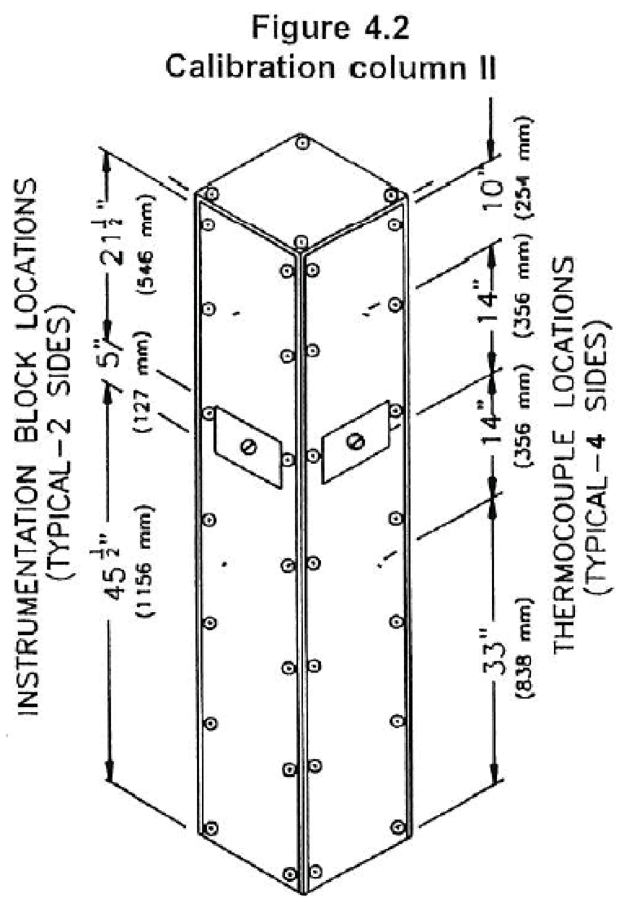

Figure 6. Dimensions of   test sample.

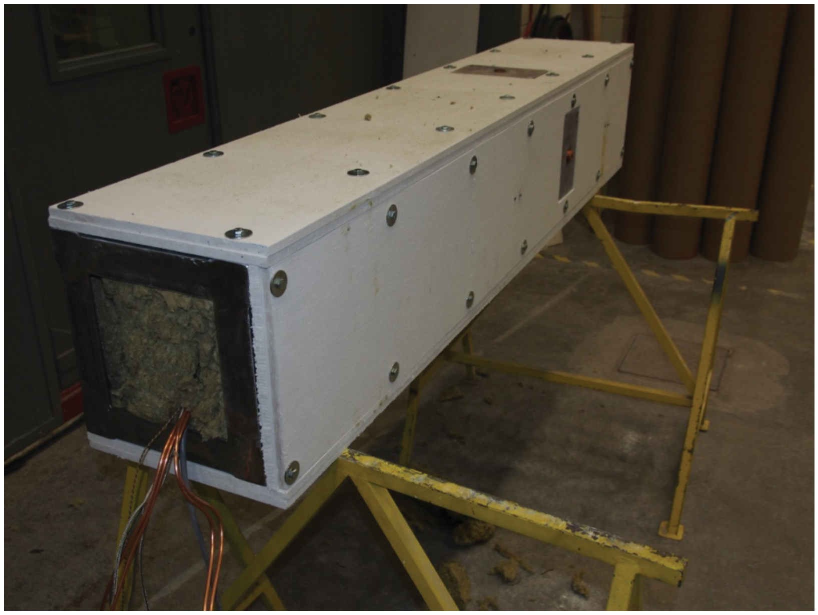

Figure 7. Constructed test sample

Figure 8. Calibration column test sample in the column furnace before the test

3.3.4 Test Results

The test was performed using the NRC column furnace. Average temperature in the furnace was controlled to meet the time-temperature curve in Figure 5 within the limit specified in 3.3.2.

Fig. 9 shows the measured heat flux during a one hour test. The figure indicates that the measured heat flux met the required minimum of 150 kW/m^2. It also indicates that the minimum heat flux for UL1709 closely met during the test. Figure 10 illustrates the results for temperatures in the furnace during the test. The results indicate that the temperatures in the furnace met the minimum and maximum temperature limits required by both ASTME1529 and UL1709. Figures 11 and 12 show the column furnace and the test samples right after the end of the test. The results showed that the requirements for the extreme fire test have been achieved.

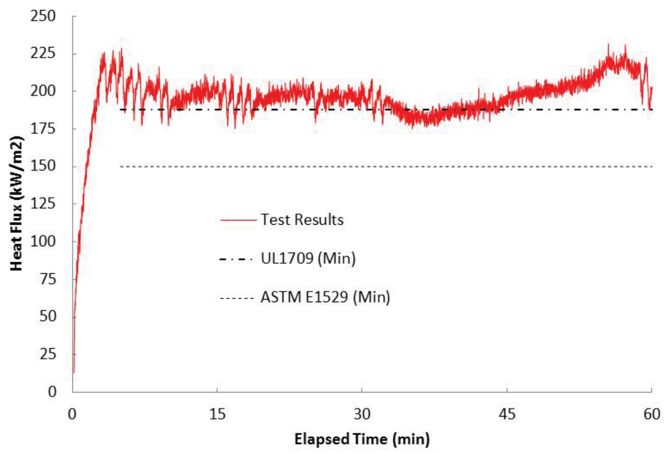

Figure 8. Heat flux measured during the test.

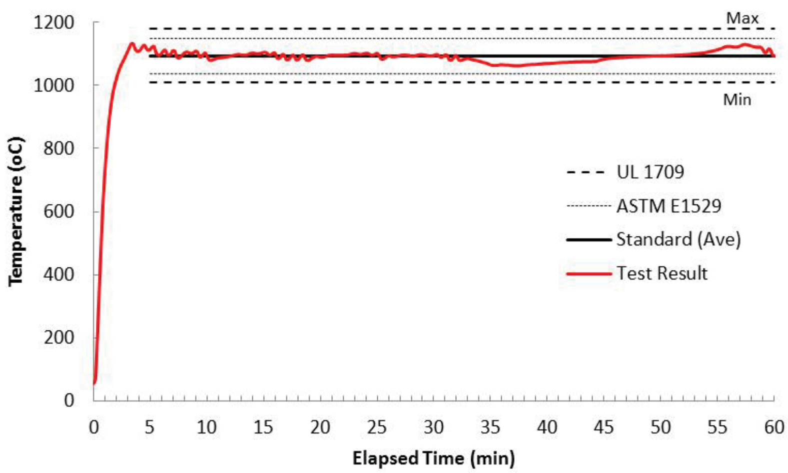

Figure 9. Furnace temperature measured during the test

Figure 10. Column furnace doors opened right after the test

11. Calibration column sample right after the test

4 Results

The outcome of this project is related to the Resilience Infrastructure community of practice: “Enhanced resilience of the physical and cyber infrastructure domains is risk and evidence based”. The immediate outcome of this study is toward “Regionally based analyses and assessments of risk and vulnerability help shape national approaches to infrastructure risk mitigation investments”.

- Impact and relevance to the identified priority and gap addressed by the project

The results of this study are expected to provide a tool to improve awareness and understanding of the vulnerability assessment of critical infrastructures to extreme fire threats to help develop decision making tools in response to and recovery from such incidents.

- Lessons learned and implementation plan

The review study showed that there are currently standards and guidelines for testing of structures to extreme fires. Three of the reviewed standard tests, UL1709, ASTM E1529 and NFPA 502 were found to be the most related standards and documents related to testing of critical infrastructures. UL1709 and ASTME1529 are very similar standards in respect to the required time-temperature curves. UL1709 does not require testing of loaded specimens and is applicable for steel structures. However, ASTM E1529 includes tests of loaded specimens and steel and concrete structures. Based on the available data on the fire severity in bridges and critical buildings, e.g. 9/11 WTC, UL1709 or ASTM1709 could be suggested for testing of these two types of critical infrastructures in extreme fire. Minor modifications were suggested to make these two standards more applicable for bridges and critical buildings. For tunnels, NFPA 502 was found to be the best standard for application in testing of tunnels to extreme fire. Since this standard, along with the RWS document, were specifically developed to test tunnels for extreme fire with minimal modification, it was recommended for application in testing of protected tunnels. For testing of unprotected tunnel linings, further tests would need to be carried out to better understand the level of fire severity. However, until then, the existing RWS curve or an equivalent curve could be used for testing of unprotected linings.

- New capabilities, partnerships and networks created through the horizontal work of the project

The test procedure developed in this study is a new unique testing tool for vulnerability assessment of critical infrastructures to extreme fires. The testing procedure was prepared and demonstrated by an extreme fire test using recently upgraded NRC testing facilities. These new competencies will enable the communities of practice on critical infrastructures to develop risk assessment and decision making tools, and protection solutions for enhancing the resilience of critical infrastructure against extreme fires. An Advisory Board was formed with 15 members from government departments, fire services, engineering and extreme fire experts, and regulatory bodies from North America. This will enable the team to first disseminate directly the outcomes through the communities of practices and to develop future research plans more efficiently.

5 Transition and Exploitation

- Transition to End Users:

The end users of the outcome of this project are the owners, manager sand and operators of transportation infrastructures, government buildings and facilities, regulatory bodies, first responders and construction industries, e.g. manufacturers of fire protection technologies. The results of this study will be shared and disseminated to these end users though workshops and presentations. Two presentations were prepared and delivered during the Advisory Board meetings at the NRC, on the results of this study. At least one paper will be produced from the outcome of this study and will be presented in a related conference. Finally, this report will be shared with the end users through DRDC.

- Follow-On Commercial Development or Recommended R&D:

NRC continues collaboration with the end users and the industry to develop and demonstrate extreme fire protection solutions for critical infrastructures to extreme fires. A recent study by NRC for the CSSP program was to identify fire protection materials and technologies for critical infrastructures to extreme fire. The results of this study and using the developed testing method and the recent upgraded NRC testing facilities, the identified potential protection solutions could be tested for application in critical infrastructures in practice. Producers of fire protection materials are interested in supporting and funding part of such studies. NRC will explore developing such a study proposal with the end-users and the industry.

- Intellectual Property Disposition:

The IP produced by this study vests in the Crown.

- Public Information Recommendations:

The results produced by this study are intended to be used by the end users.

6 Conclusions

This study reviewed current standards and information for testing of structures in extreme fire. Based on the results, a testing procedure was developed for resilience assessment of critical infrastructures to extreme fires. The following conclusions can be made based on the outcome of these works.

- There is no available standard for testing of bridges and critical infrastructures to extreme fires.
- The available standard for tunnel test (NFPA 502) uses the RWS time-temperature curve, which was developed based on protected tunnel tests. There is a lack of current test data to verify the time-temperature curve for unprotected tunnels linings.
- A procedure was developed for testing of bridges, critical buildings and tunnels in extreme fires.
- Property protection is a very important criterion for testing and design of critical infrastructure. This will have a significant impact on the recovery time of the critical infrastructures after an extreme fire incident.
- The time-temperature curve of ASTM E1529 (UL1709) was suggested for testing of transportation of bridges and critical buildings.
- Controlling both temperature and heat flux during the tests is not feasible. Therefore, only temperature needs to be controlled during an extreme fire test. Monitoring and verifying the minimum heat flux during the calibration test is required but during the test it is recommended.
- Explosive spalling could be a failure criterion for concrete elements during an extreme fire test.
- The cooling phase could have effects on the test results. Further studies are needed to determine such effects on the test results.
- A demonstration test was successfully performed, simulating a calibration test for a bridge or building column in extreme fires. Both temperature and heat flux met the criteria as required in the developed test procedure.
- When producing RWS fire using a furnace with unprotected specimen, such as concrete specimen, the heat will sink into the specimen and result in lowering the temperature of the furnace. Hence, to meet the RWS curve for a large size unprotected specimen, particularly in the first 30 minutes, might be challenging. Hence, an equivalent time-temperature curve developed for unprotected tunnels when performing an RWS curve is not feasible with a furnace.
- Experimental studies needed to quantify and verify the fire severity proposed in the test procedure developed by this project.

References..

[1] Mostafaei, H. and McCartney, C. (2012), "Vulnerability of Bridges and other Critical Transportation Infrastructure to Extreme Fire and BLEVEs", NRC Research Report No. 4259, pp. 68.

[2] Mostafaei, H., Cowalchuk, R., Kashef, A., Sultan, M., McCartney, C., and Leroux, P. (2013), “Resilience of Critical Infrastructure to Extreme Fires – Gaps and Challenges”, NRC_CSSP Research Report, pp. 74.

[3] Wright, W., Lattimer, B., Woodworth, M., Nahid, M., and Sotelino, E. (2013) “Highway Bridge Fire Hazard Assessment Draft Final Report, Prepared for the NCHRP Program Transportation Research Board of The National Academies, Virginia Polytechnic Institute and State University, pp. 492.

[4] UL 1709 (2011) Rapid Rise Fire Tests of Protection Materials for Structural Steel, UL.

[5] ASTM E1529 (2010) Standard Test Methods for Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies.

[6] CAN/ULC-S101 (2007). "Fire Endurance Tests of Building Construction and Materials", Underwriters' Laboratories of Canada, Scarborough, ON.

[7] ASTM E119 (2012). "Standard Test Methods for Fire Tests of Building Construction and Materials, American Society for Testing and Materials.

[8] NFPA 502 (2011). "Standard for Road Tunnels, Bridges, and Other Limited Access Highways", National Fire Protection Association, pp. 51.

[9] Breunese, A.J., Both, C., Wolsink, G.M. (2008). "Fire testing procedure for concrete tunnel linings", Efectis-R0695, pp. 25.

[10] Beard, A and Carvel, R, "The Handbook of Tunnel Fire Safety", Thomas Telford Press, London, 2005.

[11] EN 1991-1-2 (2002) (English): Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire.

[12] Kodur, V.K, Gu, L. and Garlock, M.,E., "Review and Assessment of Fire Hazard in Bridges" Transportation Research Record 2172, TRB, Washington D.C., 2010.

[13] ASTM E119-12, "Standard Test Method for Fire Tests of Building Construction and Materials ", American Society for Testing and Materials, West Conshohocken, PA 2012.

[14] ISO 834-1, "Fire Resistance test-Element of Building Construction-Part 1: General Requirements, Genève, Switzerland, 1999.

[15] Noble, C.R., Wemhhoff, L.D. and McMichael, L.D., "Thermal-Structural Analysis of the MacArthur Maze Freeway Collapse", ASME Summer Heat Transfer Conference, Jacksonville, FL, USA, 2008.

[16] Bajwa, C.S., Easto, E.P. and Dunn, D.S., 'The MacArthur Maze Fire: How Hot was it?, Wm2009 Conference, Phoenix AZ, 2009.

[17] Ingason, H., "Project Description and Planning of Large-Scale Tests in Runehamar Tunnel, SP Swedish National Testing and Research Institute 2003.

[18] Brekelmans, J., "Summary of Large Scale Fire tests in the Runehamar", TNO Building and Construction Research, Centre for Fire Research 2003.

[19] Prasad, K, Hammins, A., McAllister and Gross, J., "Fire Induced Thermal and structural Responses of the World Trade Center Towers", Fire Safety Science Proceedings of the Ninth International Symposium, 2008.

[20] National Institute of Standards and Technology (NIST) Federal Building and Fire Safety Investigation of the World Trade Center Disaster, Answers to Frequently asked Questions, Question 7, Http://WTC.nist.gov/pubs/factsheets/faqs_8_2006.htm.

[21] Promate, Passive Fire Protection Systems, Application & Technical Manual, Promat Asia Pacefic Organization, pp. 48, November 2012.

[22] Keltner, N.R., Hasegawa, H. K., White, J., Jr., High Temperature Accelerant Arson," Very Large Scale Fires, ASTM STP 1336, N. R. Keltner, N. J. Alvares and S. J Grayson, Eds, American Society for Testing and Materials, Philadelphia, 1980

[23] Ingason, H., "Project Description and Planning of Large-Scale Tests in Runehamar Tunnel, SP Swedish National Testing and Research Institute 2003.

[24] Brekelmans, J., "Summary of Large Scale Fire tests in the Runehamar", TNO Building and Construction Research, Centre for Fire Research 2003.

[25] Andrew H. Buchanan, Structural Design for Fire Safety, John Wiley & Sons, 2002

[26] Franssen J.M. 2007. User's Manual For SAFIR 2007a Computer Program For Analysis of Structures Subjected to Fire, University of Liege, Belgium

Annex A Extreme Time-temperature curves suggested for structural elements of bridges, tunnels and buildings fire resistance tests

Based on the available literature review (Appendix B), this section presents the suggested extreme time-temperature curve that can be used in fire resistance tests to evaluate the extreme fire performance of critical infrastructures such as bridges, tunnel lining and buildings when subjected to extreme fire conditions.

A1. Bridges

Due to the insufficiency of test results for road/rail bridges under simulated hydrocarbon pool fires in the literature, it is proposed that the structural elements (Clause 1.2) of rood/rail bridges be tested for fire resistance using the time-temperature curve of the ASTM E1529 and the test procedure be presented in this document. The suggested time-temperature curve is mainly applicable for road bridges. However, for rail bridges, until further studies are available, the same time-temperature curve could be used.

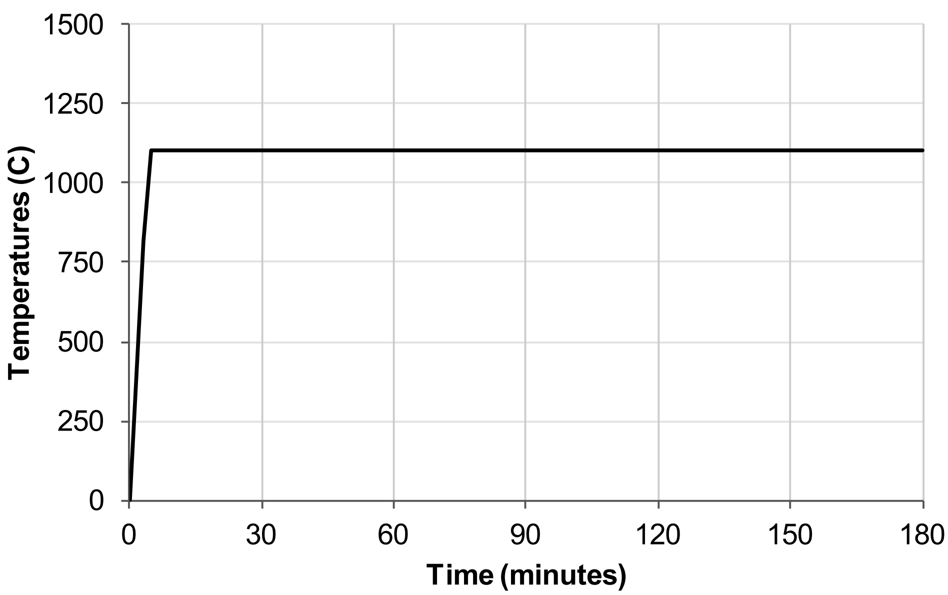

Figure 12. Extreme Fire Test Time-Temperature (ASTM E1529).

Table 1. Furnace Temperature - E1529 Test.

Time (min)	Temperature (°C)
0	20
3	815
5	1100
180	1100

A2. Tunnels

The RWS time-temperature was developed based on the Runehamar test results which showed that this level of fire severity may occur in situations where the tunnel is well insulated and the heat loss through the boundaries is minimized. As such, the RWS time-temperature is mainly applicable for testing of fire-protected tunnel linings.

For tunnels with no fire protection materials, a less severe fire curve is expected due to heat lost to tunnel linings. Therefore, further studies are needed to develop a more applicable time-temperature curve.

Currently, test facilities may not be able to achieve the RWS curve in the case of testing non-protected linings due to excessive heat loss, especially if spalling occurs. Until then, an equivalent fire severity, Appendix C, may be used for testing of non-protected specimens, when furnace facilities have challenges to reach the RWS high temperatures in time, according to the time-temperature curve.

The suggested time-temperature curve is mainly applicable for road tunnels. For rail tunnel and subways, the fire load and burring characteristics are different than those for the road tunnels. Therefore, further studies are required to define a reasonable time-temperature curve for them.

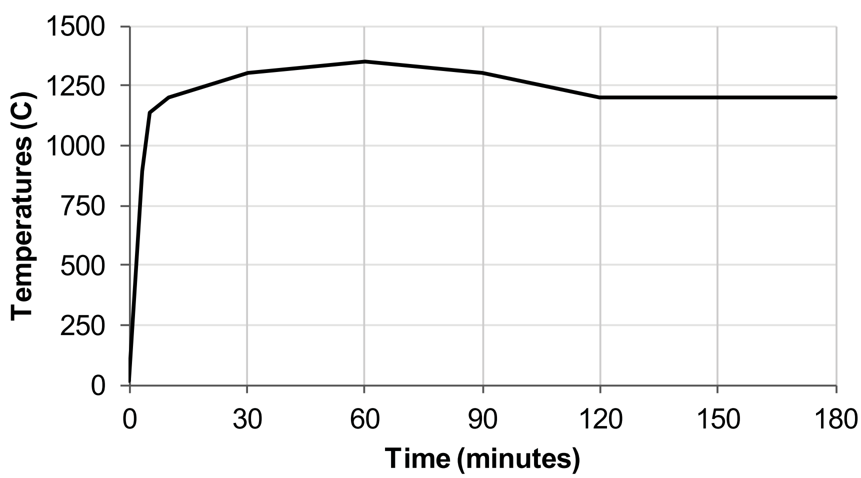

Figure 13. Extreme Fire Test Time-Temperature (RWS).

Table 2. Extreme Fire Test Time-Temperature Curve (RWS).

Time (min)	Temperatur e (°C)
0	20
3	890
5	1140
10	1200
30	1300
60	1350
90	1300
120	1200
180	1200

A3. Buildings

Based on the NIST investigation on the collapse of WTC due to airplane crashes in 2001 which contained jet fuel burning and identification of the gas hot layer temperature of 1000 °C, it is suggested that, building structural elements could be tested for fire resistance using the ASTM E1529 time-temperature curve and the test procedure presented in this document.

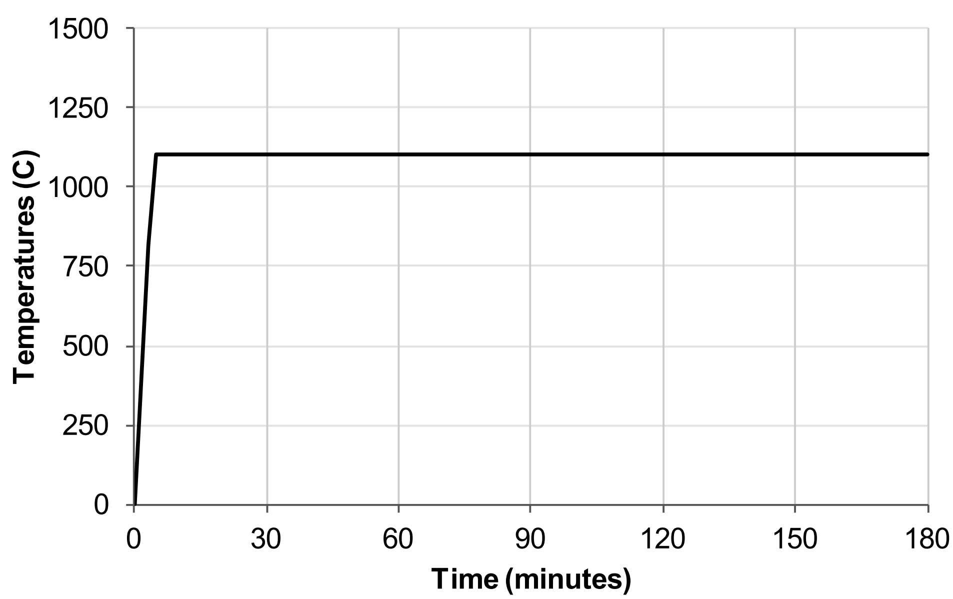

Figure 14. Extreme Fire Test Time-Temperature (ASTM E1529).

Table 3. Furnace Temperature – ASTM E1529 Test.

Time (min)	**Temperature (°C)**
0	20
3	815
5	1100
180	1100

Annex B Review of time-temperature curves for extreme fire rating test of critical infrastructures

Current fire resistance test standards, such as ASTM E119 [13], CAN/ULC S101 [6] and ISO 834 [14], are intended for a typical office and residential solid fire load. These standards are not appropriate for use to assess the fire resistance performance of structure members that are subject to extreme and fast intensity fire which resulted from hydrocarbon fuels accidents. There are a number of other fire resistance standards/design guides that could be more appropriate to assess the fire resistance performance for those structures which are vulnerable to extreme fire conditions such as ASTM E1529 [5], NFPA 502 [8], UL 1709 [4] and Efectis Nederland BV report [9].

One of the critical features of a hydrocarbon pool fire is the rapid rise of temperatures and massive heat fluxes that can expose structural members to a thermal shock which is much greater than those resulting from burning of solid fuels. The sections below are intended to provide brief information on the available standards/guides such as the scope, time-temperature, heat flux, test specimen size and failure criteria of the fire resistance standards/guides mentioned above, selection of fire exposure condition and test procedure.

This appendix presents a review of available standards and guides that are in use to assess the fire resistance of structural elements for road bridges and tunnels (NFPA 502, RWS, UL1709 and ASTM E1529) a review of a fuel truck fire incident in San Francisco bridge and full-scale experiments conducted in at Runehamar tunnel in Norway as well as the tragic incident of September 11, 2001 in World Trade Centres, New York City. Based on the review results provided in this Appendix, time-temperature curves are suggested in Appendix A which could be used to assess the resistance of critical infrastructure subject to an extreme fire conditions..

The literature search showed that there are four main documents, 3 standards and a guide, suitable for North American infrastructures. These are bridges, tunnels and high value buildings.

B1. Main time-temperature curves for extreme fire resistance tests used in the proposed test procedure

NFPA 502-11, Standard for road tunnels, bridges and other limited access highways

The scope of this standard is to provide fire protection and fire life safety requirements, minimum, for rood tunnels, bridges, elevated highways, depressed highways, and roadways that are located beneath air-right structures. This standard provides recommended practices and guides throughout the documents in different chapters. Fire protection of structural members of bridges and tunnels are provided in Chapters 6 and 7, respectively. Chapter 6 did not provide guidance on which time-temperature curve should be used, however, it provides fire protection requirements based on the bridge or elevated highway length. Regardless of bridge or elevated highway length, all primary structural members need to be protected to maintain life safety, mitigate structure damage and prevent progressive structural collapse as well as to minimize economic impact. Critical structural members need to be protected from collision and high-temperature exposure that results in dangerous weakening or collapse of the bridge or elevated highway. This chapter doesn’t provide information on fire exposure or test sample size or duration of fire exposure and failure criteria.

However, Chapter 7 on road tunnels provided information on use of the Duch Rijkswaterstaat (RWS) time-temperature curve for the fire resistance evaluation of critical structures or any HJA acceptable curve following an engineering analysis. The RWS time-temperature curve, shown in Figure 16, requirements are being adopted internationally as a realistic design fire curve that is representative of typical tunnel fires with peak HRR range from 70 to 200 MW. Oil fuel tanker produces 200 to 300 MW peak HRR. The RWS curve was developed by the Rijkswaterstaat, Ministry of Transport in the Netherlands based on the assumption that, in a worst case scenario, a 50 m3 fuel, oil or petrol tanker fire, with a fire load of 300MW, could occur, and last for up to 120 minutes. The RWS curve was based on results of testing carried out by TNO in the Netherlands in 1979.

The NFPA 502 standard states the requirements of 120 min duration of fire exposure and failure criteria of preventing concrete spalling in concrete tunnels, as well as limited temperature rise to 300 ^{o}C for protected steel or cast iron tunnel lining. For structural members, the required criteria states that the concrete temperature should not exceed 3800 ^{o}C and steel reinforcement should not exceed 250 ^{o}C assuming 25 mm minimum concrete cover. Test sample size was given as 1400 mm by 1400 mm and nominal thickness of 150 mm with exposed surface of 1200 mm by 1200 mm to furnace heat. Test should be done in a furnace that follows RWS time-temperature curve and allow surface exposure as stated above. Fire protection material should be fixed to the concrete and instrumented by thermocouples located between the concrete and fire protection material.

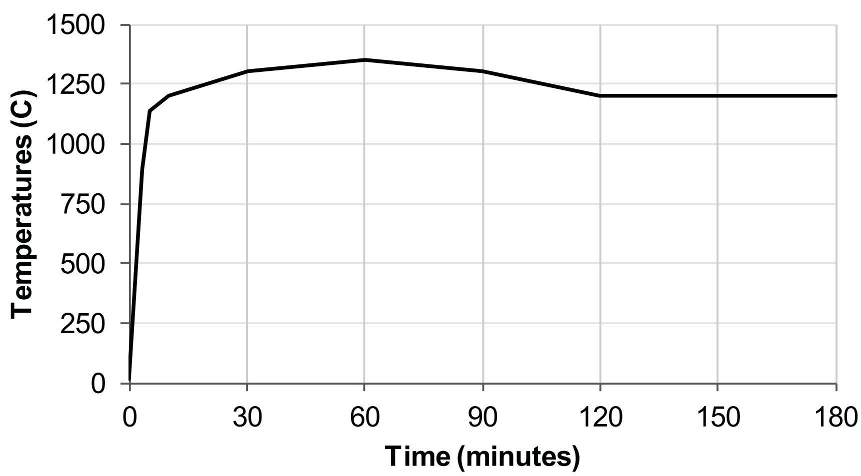

Figure 15. Extreme Fire Test Time-Temperature (RWS).

ASTM E1529-10, Standard test methods for determining effects of large hydrocarbon pool fires on structural members and assemblies.

The scope of this standard is to determine the fire-test response with and without load bearing conditions for columns, girders, beams and walls that are employed in hydrocarbon processing industry facilities under controlled laboratory conditions using a fire resistance test furnace with a specific time-temperature curve that represents fluid-hydrocarbon pool fires. This test method prescribed a standard fire exposure for comparing the relative performance of different structural members.

Fire test exposure conditions are specified in this standard which exposes the test specimen to heat flux and temperature conditions representative of total engulfment of free burning fluid hydrocarbon fueled pool fire. Within the first 5 min exposure, heat flux exposed to test specimen of 158 kW/m2 ± 8 kW/m^2. The furnace temperature that meets this heat flux is 815 ^{o}C after 3 min exposure and between 1010 ^{o}Cto 1180 ^{o}C at all times after first 5 min using not less than 5 Type

K thermocouples for walls and not less than 8 thermocouples for beam and columns. The time-temperature curve is shown in Figure 17. The specimen size for the column and beam should not be less than 2.74 m, 3.7 m, respectively. Wall specimen size should not be less than 4.65 m^2 and not less than 2.44 m height. Acceptance criteria for load bearing columns and beams is that the column or beam shall sustain the superimposed load during the fire endurance test for a period equal to that for which rating is desired. Conditions of acceptance of walls for a time period equal to that for which rating is desired are:

a. Wall assembly shall have withstood the fire endurance test without passage of flame or gases hot enough to ignite cotton waste, and

b. Thermocouples average temperature readings shall not exceed 139 ^{o}C above the initial reading, or any single thermocouple reading shall not exceed 181 ^{o}C above the initial thermocouple reading.

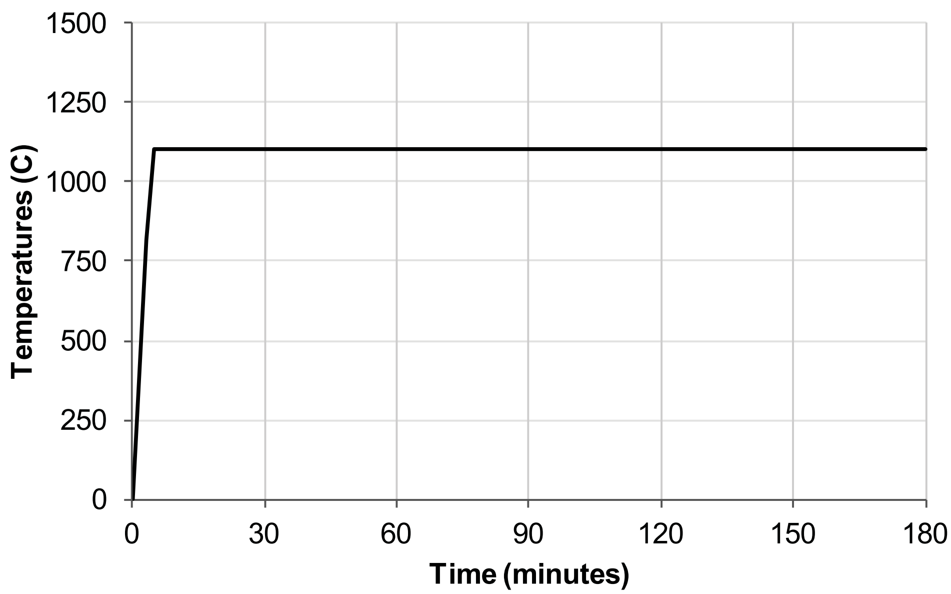

Figure 16. Extreme Fire Test Time-Temperature (RWS).

UL 1709, Standard for safety- rapid rise fire tests of protection materials for structural steel

This standard test method is intended for the thermal resistance evaluation of protective material applied to steel structural members in a rapid-temperature-rise fire without load bearing conditions. The test requirement for rapid fire includes a rapid heat flux of 204 $kW/m^2 \pm 16\ kW/m^2$ and a rapid temperature rise of 1093 ^{o}C in 5 min from start of the test and then remains constant to the end of the test as shown in Figure 17. Some allowance for these conditions are provided. The allowance includes the furnace control in such a way that the area under the time-temperature curve be within 10% of the corresponding area under standard curve for a test duration of 60 min or less and within 7.5% for a test longer than 60 min but not longer than 120 min.

In UL 1709 standard, the performance criteria is set such that the temperature between the steel and protective material during the period of fire exposure for which classification not to exceed 538 ^{o}C on the average of thermocouple readings and not to exceed 649 ^{o}C on a single thermocouple reading. Test sample is in form of a square steel tube 152 mm by 152 mm and

610 mm long. The thickness of steel tube is 4.8 mm and tube is to be provided with steel caps and covered with the protective material being investigated.

2008-Efectis-R0695 Netherland BV, guide for fire testing procedure for concrete tunnel linings

The Netherlands requires that road tunnels underneath open water be resistant against a hydrocarbon-fire according to the RWS curve. The Efectis Netherland report R069 [9] provides a guide for test procedure for tunnel lining, which described a test on a concrete slab with fire protection, to be exposed to the RWS fire curve. The report described two tests (geometry, loading, fire protection) and test procedure and performance criteria. Test 1, for spalling behaviour of concrete (spalling test) and test 2, for measuring concrete temperature at the exposed and at reinforcement (thermal insulation test). To prevent or mitigate damages result from fire, the report stated a few measures such as avoid or limit concrete spalling, concrete temperature at surface and in and around reinforcement, concrete unexposed surface as well as limit propagation of concrete cracking into the unexposed side (cold zone).

a. Spalling test

The report defines parameters such as test specimens which include protected and unprotected concrete slab, column and beam with length and width set to 6-8 times actual field thickness with reinforcement as per tunnel lining design. Test specimens to be fire tested in accordance to RWS fire curve as shown in Figure 18 with orientation as per it represents (i.e. wall specimen should be tested in wall furnace).

For concrete under compression in an underwater tunnel or other tunnels, the requirements are:

Concrete surface temperature should be less than 380 ^{o}C

Steel reinforcement should be less than 250 ^{o}C

For concrete under compression in other tunnels, the requirements are

Concrete surface temperature should be less than 380 ^{o}C with 25 mm concrete cover

Steel reinforcement should be less than 250 ^{o}C

The concrete spalling is never allowed to be more that superficial.

b. Thermal insulation test

The objective of this test is meant to assess the thermal insulating capacity of fire protection system. The concrete lining type specimen should not sensitive to spalling. The dimension of the test specimen is 1450 mm by 1450 mm and nominal thickness of 150 mm with top and bottom steel reinforcement concrete slab. The requirements for this test are similar to those of spalling tests.

B2. Other time-temperature curves for extreme fire resistance tests

The Hydrocarbon (HC) Curve

The HC curve is a simulation of a ventilated oil fire with a rapid temperature increase presented by Eurocode 1 [10]. The curve represents combustible hydrocarbons and is applicable where petroleum fires might occur, i.e. petro or oil tanks etc. The maximum temperature in this curve is about 1080 ^{o}C as shown in Figure 18.

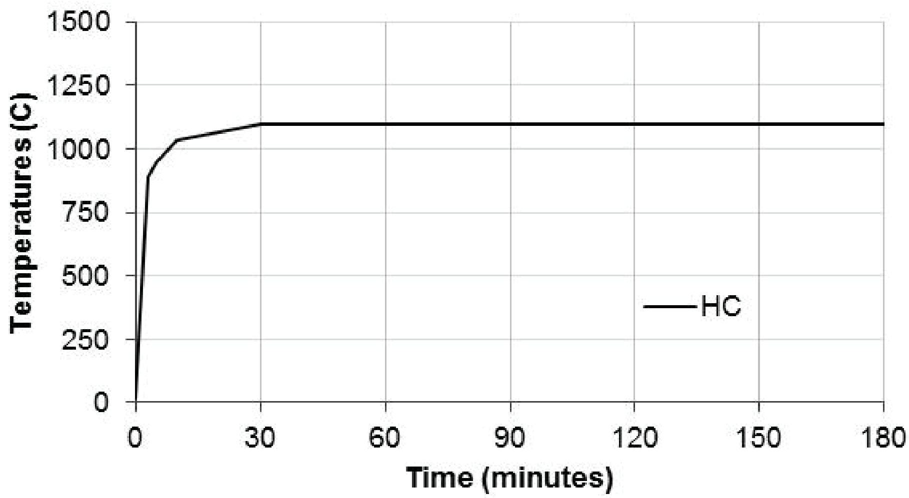

Figure 17. Hydrocarbon (HC) Time Temperature Curve.

The Modified Hydrocarbon (MHC) Curve

The MHC time-temperature curve is used, by French regulations, to test fire resistance of tunnel structures or lining with a maximum temperature of 1300 ^{o}C as shown in Figure 19. This curve is slightly more severe than the ASTM E1529 and UL 1709 hydrocarbon curve after 3 min but has the same temperature gradient in the first 3 min as the ASTM E1529 and UL 1709 time-temperature curves. It is more or less similar to the RWS curve; however, its peak temperature is about 50 ^{o}C below the RWS curve.

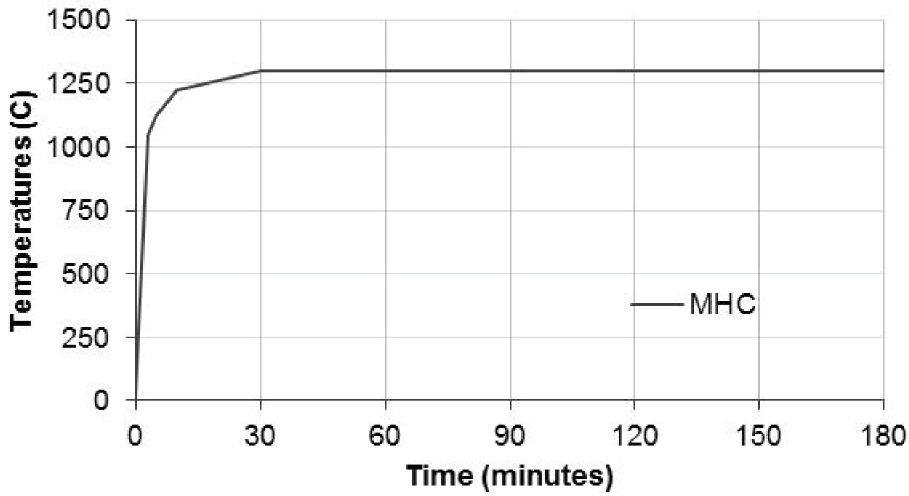

Figure 18. Modified Hydrocarbon (MHC) Time Temperature Curve.

The RABT Curve

This is the German’s time-temperature curve for fire resistance testing of structures and linings of road tunnels. This curve is an outcome of tests conducted by Eureka project [21]. The temperatures rises very rapidly to 1200 ^{o} C in about 2 min and then remains constant to 60 min exposure and then drops to 550 ^{o} C afterward for another 60 min as shown in Figure 20.

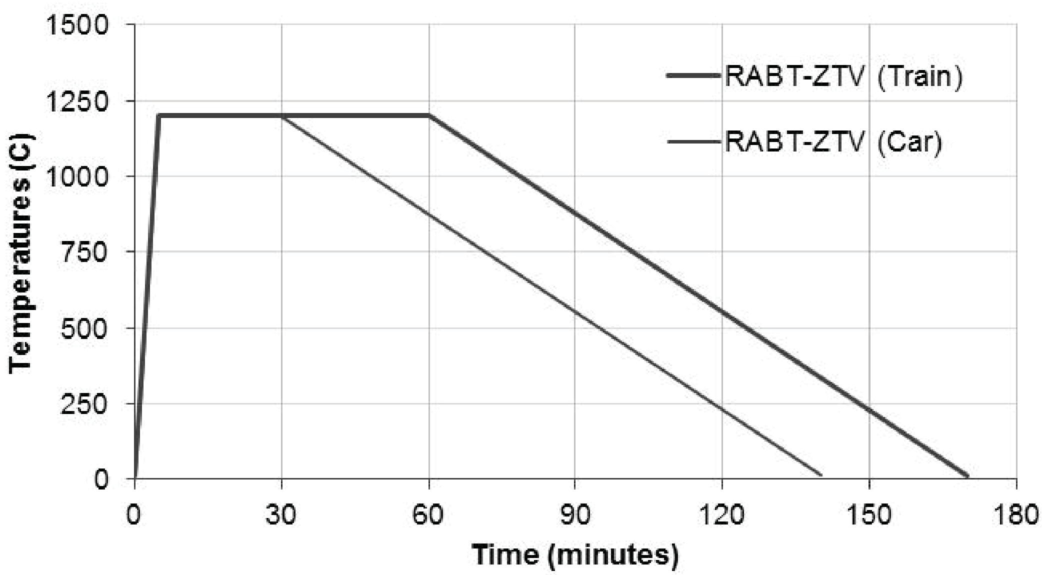

Figure 19. RABT Time Temperature Curve.

B3. Time-temperature curves comparison

The time-temperature curves of ASTM E1529, UL 1709, RWS, RABT, RABT, HC and MHC are presented in Figure 21 for comparison purposes. In all curves, the temperature rises steeply in the first 5 min. The RWS curve is the most severe curve up to 90 min, however, after 90 min, the MHC curve is the most severe curve. The RWS, MHC and RABT curves are more severe and hard to achieve in fire resistance test furnaces than the ASTM E1529 and UL 1709 curves.

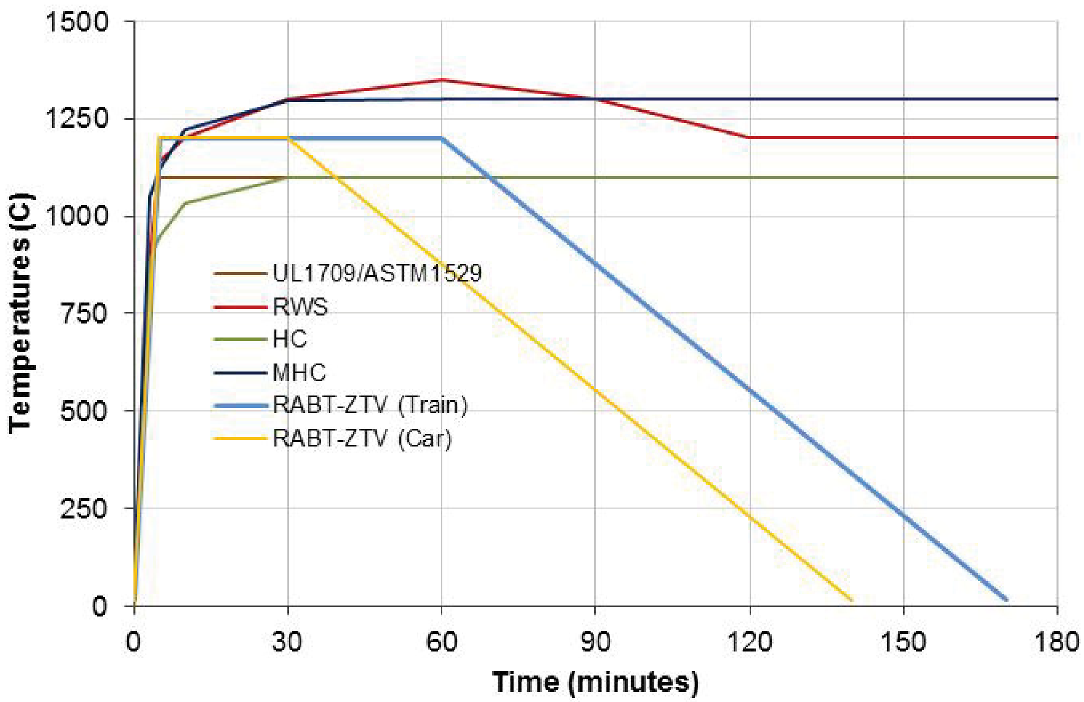

Figure 20. UL 1709 and ASTM E1529, HC, MHC, RWS and RABT Time Temperature Curve.

B4. Fire severity in bridges, tunnels and buildings subject to extreme fire conditions

A brief literature review was carried out to determine the typical fire severity for extreme fire conditions in bridges, tunnels and buildings' fire incidents/full-scale test. For bridges, there is no full-scale test reported in literature but there are two studies on the San Francisco MacArthur Maze road bridge fire incident. For tunnels, there is a full-scale Runehamar road tunnel test which was conducted in Norway in 2003 and provided similar fire severity results as the RWS time-temperature curve in extreme fire conditions. For critical buildings, there is a study on the World Trade Center tragedy in September 2001 that can be considered as an extreme type of fire conditions in buildings. The following sections provide a brief overview on the extreme fire conditions studied in this report.

Extreme Fire Conditions in Bridges

There is no full-scale test conducted in literature on extreme fire at bridges, however, to determine the extreme fire severity in bridges, there is a study on a major fire crash that occurred in San Francisco in 2007.

The San Francisco MacArthur Maze Freeway fire accident occurred in 2007 as a result of a tractor-trailer rig carrying 8600 gallons of fuel overturned on Interstate 880 in Oakland, CA. Initial media reports of the accident cited sources at the scene estimated that the fire reached temperatures as high as 1650 ^{o} C [12, 15], however, there is no direct temperature measured at the fire scene. After the accident, there were several studies conducted to investigate the bridge collapse due to fire and two of them are reported below.

In a study by Noble, C.R, et al [15] on the thermal structural analysis of the San Francisco MacArthure bridge showed that the bridge collapse occurred due to weakened steel superstructure that failed in 18 min. In this study, the coupled thermal-structural finite element analysis was performed using a mass scaling methodology in thermal analysis to reduce the overall simulation time. The analysis used showed that the structural failure occurred due to thermal softening of steel at approximately 18 min using a fixed fire temperature of 1200 ^{o}C and thermal properties. When temperature–dependant thermal properties and fire temperature of 1200 ^{o} C were used, the failure occurred at 10 min and 16 min for south and north spans, respectively.

In a second study by the US Nuclear Regulatory Commission, of the same fire accident and published by Bajwa, C. S. et al [16], titled "The MacArthur Maze Fire: How hot was it?" This study examined the samples collected from the collapsed bridge using the traditional metallurgical methods. Based on the metallurgical analysis that were carried out, it was reported that the steel structure was exposed to a temperature that was close to 1000 ^{o}C.

Extreme Fire Conditions for Tunnels

Fortunately, there are some small-scale and 4 full-scale fire tests found in literature that were conducted in 2003[17, 18]. The small-scale tests were carried out at the SP Swedish National Laboratory while the full-scale tests were carried out at the Runehamar tunnel in Norway.

The objectives of small-scale tests were to obtain data such as fire behaviour, heat release rate, smoke production and hazardous gases for several combustible commodities that were used in the full-scale tunnel test program. The combustible commodities include cartons with PS cups, mixture of wood pallets and plastic pallets, and mixture of wood pallets.

The objectives of the four large scale tests (UPTUN project with 41 partners from 17 European countries) was to produce data on fire development and fire spread, using a simulated set-up of a semi-trailer cargo, and heat exposure to tunnel linings in the vicinity of the fire site inside the tunnel. The full-scale tests provided data on smoke spread in the tunnel, upstream and downstream of the fire, conditions under which firefighters with breathing apparatus may have to work with, smoke development from various types of fire loads, gas temperature and heat fluxes close to the fire site inside the tunnel and heat release rate. The fire load for the full-scale test is as follows:

Test-1, with 10911 kg combustibles (wood pallets and plastic pallets);

Test-2, with 6853 kg combustibles (wood pallets and PUR mattresses);

Test-3 with 8500 kg combustibles (real furniture);

Test-4, with 3120 kg combustibles (corrugated paper cartons, unexpanded polystyrene cups and wood pallets).

Tests were performed with a fire light-up in a simulated semi-trailer set-up. The test result that is relevant to this report is the gas temperature in the vicinity of fire. Test-1 with the highest fire load produced the highest temperature of 1365 ^{o} C for the longest period of time at 30 min before it reduced down to 300 ^{o} C at 60 min. Tests 2, 3 and 4 produced a lower temperature of 1250 ^{o}C and lower durations of fire exposure compared to Test 1. The time-temperature curve of Test-1 followed the ASTM E1529 hydrocarbon curve in the initial 3 min and then followed the Dutch RWS curve that was mentioned above afterward.

In the simulated tests mentioned above, where the fire was located 560 m away from one end of the tunnel, the effect of fire location inside the tunnel i.e. closer to the tunnel entrance was not investigated to determine the fire severity where a large amount of air could be sucked-in.

Extreme Fire Conditions in Buildings

The September 11, 2001 airplane attack on the World Trade Center (WTC), in New York City, represents an extreme fire condition in buildings. However, the WTC buildings were not designed for this type of petrol jet fuel fire conditions, but rather were designed to meet ASTM E119 building standard requirements.

A study [19] was conducted to investigate the fire induced thermal and structural response of the World Trade Center Towers showed that, the hydrocarbon fires generate temperature up to about 1100 ^{o} C; however, NIST [20] reported that the maximum upper hot layer air temperature was about 1000 ^{o} C in the WTC fire.

In a different project, an extreme fire experimental program was carried out to investigate arson in buildings that involved fast fire growth [22]. The main purpose of the study was to investigate the risks posed by such fires to fire fighters, as part of a forensic study. The study indicated that a number of unusual arson fires was reported for buildings involving liquid fuel accelerant, more severe than the typical building fires. Some of these fires caused premature structural failure. Based on the temperatures reported at the ceiling during the tests, one may observe an average max temperature of 1100 ^{o}C.

The study confirmed that the results resembling some of the suspected arson fires using accelerant mixtures.

Annex C Temperature-based equivalency fire severity approach

When testing concrete specimens directly to fire without a protection layer, the furnace facilities may have challenges to reach the RWS high temperatures in time, according to the time-temperature curve. This would be due to the amount of heat absorbed by concrete until it heats up. In a real fire scenario, the same phenomenon is anticipated; for the same amount of fuel, a tunnel that has fire protection or insulation would be experiencing a higher temperature, as it was the case for the Runehamar's tests[23, 24], than that of a concrete tunnel without any protection. In such a scenario, until further experimental studies are available, an equivalent fire severity based on the temperature of the steel bars [25] could be employed using RWS and ASTM1529 time-temperature curves as described here. Using this method, one may employ the ASTM1529 time-temperature curve instead of RWS time-temperature curve but with longer test duration. The equivalent fire severity method is described here:

Steps:

1. Using validated software for heat transfer analysis of concrete structural elements, model the specimen according to the size, load and support conditions required for the extreme fire resistance testing, as described in the guide.
2. Run heat transfer analysis of the specimen by exposing it to RWS time-temperature curve on the side as required by the extreme fire resistance testing guide.
3. Obtain time-temperature curve response in the main steel bars, on the exposure side.
4. Repeat steps 2 and 3 for the same steel bars but when the specimen is exposed to ASTM E1529 time-temperature curve on the same side.
5. Determine the ASTM E1529 equivalent duration:

Obtain the temperature of the main steel bar, T_{eq}, at the required extreme fire resistance time, t_{RWS}, from the results of RWS analysis in step 3.

From the results of the ASTM E1529 analysis in step 4, determine the time, t_{E1529}, at which the same main steel bar experiences the same temperature, $T_{eq.}$

t_{E1529} is defined as the ASTM E1529 equivalent duration.

Example

In this example, SAFIR software [26] was employed for the analysis. A slab specimen, 1.15 m by 1.15 m and 200 mm thick was considered, as specified in Efectis 2008 [9]. Figure 22 shows the FE modeled section of the specimen.

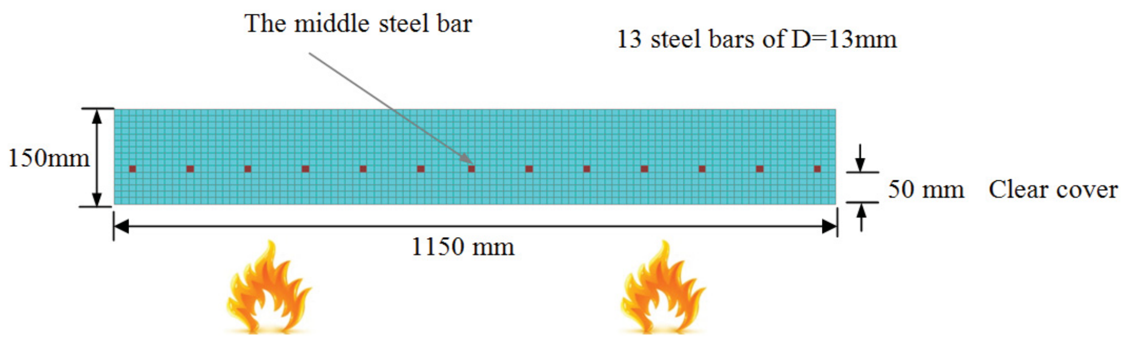

Figure 21. Cross section of the reinforced concrete test specimen

The section was first exposed to RWS time-temperature curve from underneath. A heat transfer analysis was performed for the section subjected to the RWS curve using SAFIR and the temperatures for the steel bars were obtained. Figure 23 shows the time-temperature curve result for the middle steel bar, Figure 22.

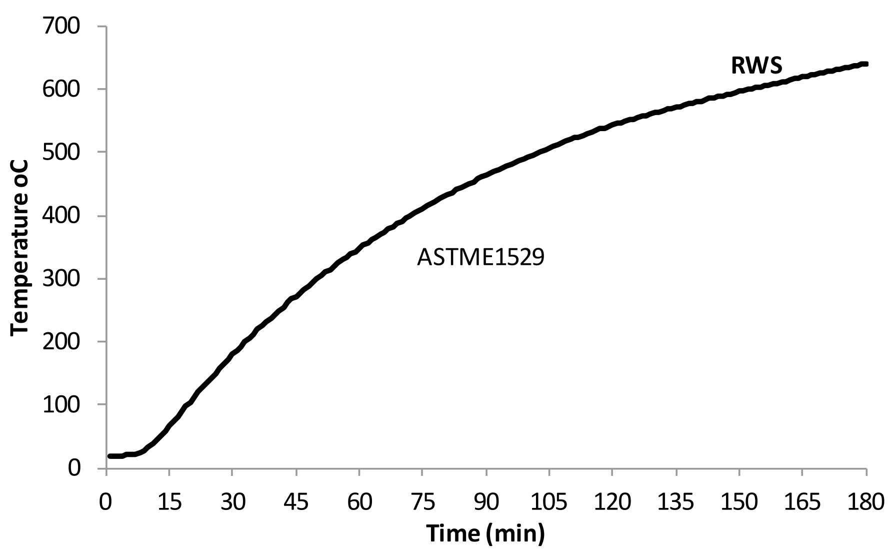

Figure 22. Time-temperature curve results for the middle steel bar when the specimen is exposed to RWS

The heat transfer analysis was repeated for the same section, but this time, when the specimen was subjected to ASTM E1529 time-temperature curve from underneath. The time-temperature curve results for the same steel bar are plotted in Figure 24.

Figure 25 shows both Figure 23 and Figure 24 and how ASTM E1529 equivalent duration is obtained. As indicated, the ASTM E1529 equivalent duration is t_{E1529} = 158 minutes. In other words, if the requirement is to test the specimen for t_{RWS} = 120 minutes (two hours) exposed to RWS curve, an equivalent fire resistance test would be obtained when the same specimen is tested exposed to ASTME1529 curve for t_{E1529} = 158 minutes.

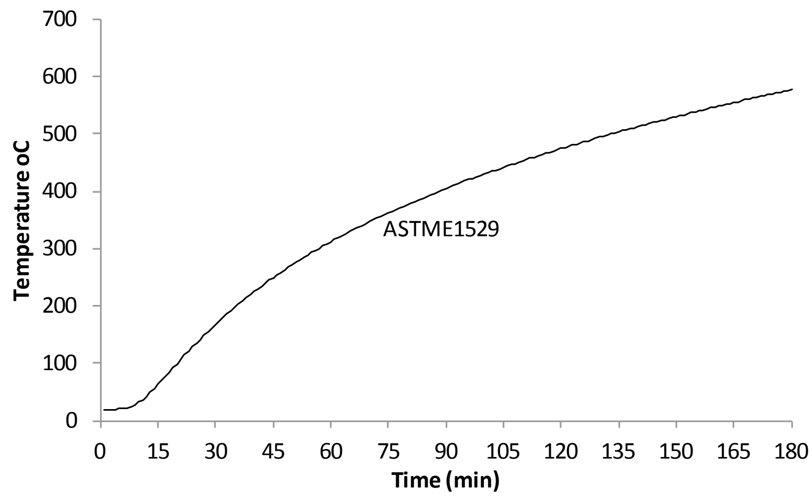

Figure 23. Time-temperature curve results for the middle steel bar when the specimen is exposed to ASTME1529

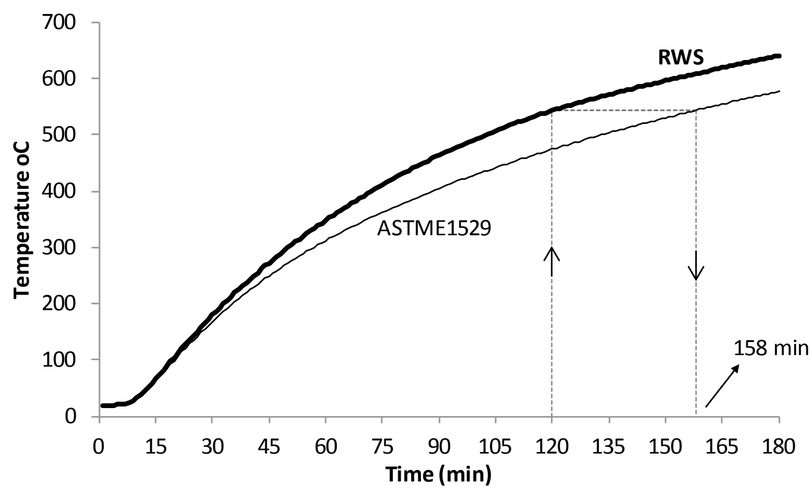

Figure 24. Determining the equivalent fire severity with the ASTM E1529 curve

Annex D Requirements for Property Protection

If property protection is a requirement for the design of concrete columns, beams, slabs, and walls, the following requirements would be applicable. For instance, recovery of an important bridge after a fire incident is very critical to minimize the economic and social impact on the communities. In such scenarios the concrete structural elements shall be evaluated for the integrity criteria.

Integrity criteria for concrete elements are defined so that the repair of the structure after fire would be minimal. The main criteria would be (until further studies are available):

I) when the spalling is greater than 10% loss of column, beam, slab, or wall thickness (in the direction of spalling) as measured at the deepest points of spalling;

II) when the temperatures on the steel reinforcing exceeds 250 °C for any single measurement;

III) when explosive spalling occurs.

For steel structures, further studies are needed to investigate if the 250 degree C criterion for steel temperature would be a reasonable or a conservative criterion.

Annex E Advisory Board Meeting Minutes

E.1 Advisory Board Meeting 1

Time: Wednesday, 18 Dec 2013, 1:00pm – 3:00pm (Ottawa Time)

Location: NRC building M-59, 1200 Montreal Road, Ottawa, Canada - 2nd Conf. Room

ATTENDEES

William Connell, Ron Cowalchuk, Rae Dulmage, Gary English, Lynne Genik, Dwayne Goudie, Ned Keltner, Mohamed Sultan, Martin Vermeer, and Hossein Mostafaei

MEETING ITEMS

Item 1: Welcome to Advisory Board (AB)

Introduction

Mohamed expressed the main objectives and steps (more information from Mohamed's memo will be included)

Mohamed delivered a presentation titled "Test Methods of rating the resistance of critical infrastructure structural members in extreme fires".

Ned: Large scale pool fire tests were done at Sandia National Laboratories. Tests were run using JP-4 and later JP-8 fuel; the heat release rate was over 500 MW with average flame heights of 125 feet. Temperatures and velocities were measured at elevations of up to 50 feet. Heat flux was measured 1 m to 6 m from the pool surface; the largest calorimeter was 1.6 m OD x 6 m long and weighed 10 tons. Sandia and NASA published reports on large pool fires (I can provide copies of technical papers on these tests or the complete Sandia reports to anyone who is interested).

Sandia and SINTEF in Norway jointly developed and validated a large-scale, CFD fire model. Norway's interest was offshore platform safety. The 3rd and 4th generation codes are called VULCAN and FUEGO. Sandia also uses faster-running fire models in tandem with the CFD codes for probabilistic risk assessments. Codes, such as FBS, from NIST, or FLUENT are some examples.

Martin: The fire scenarios under the bridge and on the bridge would be different.

Hossein: The fire underneath is a worst case scenario compared to that on the bridge. However, more studies are needed for fires on the bridges to understand fire severity.

Martin: RWS reaches higher temperatures than the ASTME1529, therefore, have different effect on concrete structures.

Rae: ISO 834 has a supplementary part including jet-fire tests. Types of fuel is important. Ethanol for instance could have a different fire severity.

Mohamed: Gasoline could be a worst case scenario; therefore, it is the proposed curve for extreme fires.

Hossein: The main fuels are gasoline and propane or any other fuel that produces the same level of fire load.

Ned: Alcohol pool fires are not the same as hydrocarbon fires. Directional Flame Thermometers (DFTs) can be used for comparison tests to explore heat flux measurement for bridges. We will be revising a new ASTM Standard for Using DFTs to Measure Heat Flux. We expect approval by roughly June.

Ned: A large diesel or gasoline pool fire would achieve roughly the same temperatures and heat fluxes. Laboratory test furnaces have challenges in achieving fast rising fires. (Compare the heat fluxes in E1529 to those in the attachment)

Lynne: How is this project in line with the Canadian Safety and Security Program (CSSP)?

Ron: This project will help develop a test procedure that will enhance resilience of critical infrastructures and particularly the transportation infrastructures against extreme fire threats, mainly security aspect, a gasoline tanker would be used as a weapon to attack a critical infrastructure.

Hossein: None of the bridges are designed for fire. After most of fire incidence, the owners decided to demolish the bridge and rebuild the entire bridge due to lack of knowledge and information and that resulted in a very long rebuilding recovery of the critical infrastructure and caused significant socio economic impact on the community.

Gary: post fires actions are important. Data is needed to understand how many fires occurred on the bridges.

Lynne: Data on number of fire incidents on critical infrastructures are needed.

Lynne: Since we have a member from the US, we could invite a new member Fire Portfolio from DRDC.

Bill: NFPA 502 is intended to apply to both road tunnels and bridge structures but structural protection guidance on bridges is very limited. Fire threat, risk, and tolerance of loss will be different depending on the specific structure and the potential fire scenarios. How we have been dealing with tunnels could also be applicable in the bridges. There is no real technical expertise in this area on NFPA 502 committee.

Gary: we need people with bridge fire knowledge to join NFPA 502 standard committee.

Hossein: Participation in the NFPA 502 related to the area of bridge/tunnel fire would be in line with our current research.

Martin: RWS could be good for rail tunnels but not for subway tunnels as fire load is different. Not much information is available for subway tunnels.

Bill: RWS would be considered applicable for cargo/freight rail tunnels.

Rae: A presentation could be delivered at the annual Fire Marshal meeting about April 28 and 29, 2014.

Rae: More work is needed to prepare information for standard.

Hossein: This project is only to study available information in literature and the project outcome is not to be a standard but rather recommendations with information that will be useful for standards development later on.

Ron: Target structures would be government buildings, embassies, important government buildings, transportation infrastructure buildings.

Ned: Some work was done on high-temperature accelerants with the Seattle Arson Squad. Using approximately 500 pounds, put a reasonably sized retail store into flashover in 2 minutes and had it fully involved in 3 minutes. Similar amounts of such fuel could seriously impact the buildings.

Ned: Having heat flux measurements would be valuable information for developing future models.

Mohamed: NRC can run tests to model and measure heat flux as well.

Ned: Sandia National laboratory studies showed that exposure of concrete to high heat flux is important.

Hossein: UL1709 and RWS control the tests by temperatures only. NRC can measure and check the heat flux for calibration purposes. During the test, temperatures could be controlled. However, measuring heat flux is still useful data for computer modeling.

Next Step:

Hossein: The minutes will be sent out for your review. Please provide your input on the test procedures by email. Next meeting will be mainly on the property protection requirements and test procedures.

Wished merry Christmas and Happy New Year 2014

ADDITIONAL COMMENTS AFTER THE MEETING

Ned:

1) There is a paper that shows measurements made with a large, horizontal plate calorimeter in a short test– it was mounted 12.5 feet above the fuel surface. This paper also provides correlations for estimating temperatures and heat fluxes in pool and spill fires based on the size of the fire and the location of an object or surface in the fire. I will try to find another paper that describes how physically-large, thermally-massive objects alter the heat transfer.

2) I believe continuous heat flux measurements are needed to support your risk assessments.

In extensive work on pool fires, using temperature measurements to estimate heat flux in pool fires provided answers that were accurate to only a Factor of 2. That is a big range for risk assessments

E.2 Advisory Board Meeting 2

Time: Wednesday, 29 Jan 2014, 1:00pm – 3:00pm (Ottawa Time)

Location: NRC building M-59, 1200 Montreal Road, Ottawa, Canada - 2nd Conf. Room

ATTENDEES

William Connell, Gary English , Dwayne Goudie, Ned Keltner, Martin Vermeer, Dave Matschke, Steve Ernst, Ahmed Kashef, Mohamed Sultan, and Hossein Mostafaei.

MEETING ITEMS

Members Introduction

Mohamed welcomed the members to the second and last meeting of the Advisory Group on the project. He also thanked the members for their input to Hossein's draft report that was circulated after the last meeting. He briefly explained about the purpose of the meeting, that the members need to focus on the proposed test procedure and property protection.

Ned: suggested that heat flux meters need to be added to the test procedure to measure heat flux during the tests. Also, he mentioned that in some scenarios, such as the nuclear plants test procedure, specific heat flux devices are required which need to be assessed during the test.

Hossein: test furnace can be controlled either with temperature or heat flux, but temperature is the likelihood parameter that is to be considered in controlling test furnace. He suggested to measure heat flux to insure it's within the range specified by the ASTM E1529 standard.

Ned: Depending on the size of the specimen, is it possible the heat flux could change?

Ahmed: suggested it's fine to control the furnace with temperature and at the same time monitor the heat flux.

Ned: for calibration this could be a criteria, but during the test still monitoring heat flux would be needed.

Ned: Tests could be done with real tank car fire to estimate the heat flux for bridges.

Martin: we never measured heat flux because the furnace condition. The radiation in the furnace would satisfy the requirement for heat flux.

Ned: in the coastal structure tests, the heat flux at the floor was high and was low at the ceiling and this would be for wall and column furnaces. If you control only temperature the heat flux could not be evaluated.

Martin: in RWS, the deviations are checked for both temperatures and area under the curve temperature time curve (±100 0C).

Ahmed: RWS want to have a large size fire. In ASTM, large furnaces are employed such as floor furnace; you want to make sure that you can achieve the high temperature.

Ned: In addition to heat flux meters, using DFT would provide the opportunity to have a second heat measurement too.

Ned: In E1529, sheathed thermocouples are used for furnace temperature and DFT are used to determine heat flux inside furnace.

Hossein: said, Type B is very expensive.

Martin: we used k-type TCs in RWS rather than B-type.

Ned: there are also Type N thermocouples for high temperatures.

Ned: E119 would describe “Furnace Uniformity” that could help in this test procedure.

Ahmed: Superficial spalling needs to be defined.

Ahmed: when spalling occurs and steel reinforcement is exposed to heat, that could be a failure criteria.

Ahmed: The decay phase of fire also needs to be performed by the furnace to have more realistic performance and spalling effects.

Gary: questioning the practices of cooling the concrete structure exposed to heat by water spray could cause more spalling?

Mohamed: said based on what we know, there are 2 that parameters can cause spalling: bore pressure build up and temperature gradient at the concrete surface that causes deferential tension and compression stresses at the surface and by spraying water on hot concrete surface that will result in reducing this stress deferential and reduce the spalling effect.

Ahmed: heat release rate is different from heat flux. For normal tunnels three lanes 100MW fire size could be produced.

Martin: Spalling needs to be checked after 24 hours (3 cm), since during the cooling phase spalling could continue.

Martin: The purpose of RWS is that if the specimen passes the test, after any fire it would need only minor repair or change of the fire protection only.

Hossein: would compression test after the test provide valuable data or is it good criteria?

Martin: this is not performed for RWS test.

Ahmed: we did compression tests for heated samples and that could provide valuable information on residual strength.

Ahmed: in test procedure, you need to define superficial spalling in terms of thickness.

Ahmed: explosive spalling could be criteria too.

Mohamed: said in our next step, we will be distributing the minutes of this meeting to everyone and as well the draft of the testing procedure based on today’s discussion for any additional input.

Mohamed thanks every participant for their time and input and adjourns the meeting at 3:00 pm.

Follow up Comment:

Rae: In my experience, the calibration actions are critical to avoid error or misapplication. We should include the need and the means for stabilization. This would need to be clearly stated with any considerations/conditions.

Annex F Project Team

Pierre Meunier, Head, Boader and Critical Infrastructure Resilience, S&T, Defence R&D Canada- Centre for Security Science, was the Cluster/CoP lead of this project and contributed greatly in the development and implementation of the research plan. Dr Darek Bingo was the researcher representative from S&T, Defence R&D Canada- Centre for Security Science in this study.

Hossein Mostafaei, PhD, P.Eng., a Research Officer of the Fire Safety of the National Research Council Canada led and managed this project.

Ron Cowalchuk and Dwayne Goudie from Transport Canada were experts and representatives as to the end-users and contributed in the development of the tasks and dissemination of the outcomes of this project.

The advisory board members:

- Darek Baingo - Defence Research and Development Canada, Ottawa
- William Connell - Parsons Brinckerhoff, Boston
- Ron Cowalchuk - Transport Canada, Ottawa
- Rae Dulmage - Underwriters Laboratories of Canada, Ottawa
- Gary English - Seattle Fire Services, Seattle
- Steve Ernst - Federal Highway Administration, Washington
- Lynne Genik - Defence Research and Development Canada, Ottawa
- Dwayne Goudie - Transport Canada, Ottawa
- Ned Keltner - ASTM - Albuquerque, NM
- Ahmed Kashef, NRC, Ottawa, ON
- Dave Matschke- Defence Research and Development Canada, Ottawa
- Pierre Meunier - Defence Research and Development Canada, Ottawa
- Mohamed Sultan (Chair) - NRC, Ottawa, ON
- Martin Vermeer- Efectis, Rijswijk, Netherlands.

Hossein Mostafaei was the secretary of the advisory board.

NRC Research team contributed in the development of the test procedure were:

Ahmed Kashef, Acting Director, Fire Safety, National Research Council Canada

Mohamed Sultan, Senior Research Officer, Fire Safety, National Research Council Canada

Hossein Mostafaei, Research Officer, Fire Safety, National Research Council Canada

NRC Technical Officers contributing in the demonstration test:

Patrice Leroux (Chief Technical Officer), Robert Berzins (Technical Officer), Eric Gibbs (Technical Officer), Pier-Simon Lafrance (Technical Officer) and Karl Gratton (Technical Officer).

Annex G Project Performance Summary

Technical Performance Summary:

The two main objectives of this project include:

Objective 1: To develop a procedure/too for extreme fire resistance assessment of critical infrastructures, e.g. bridges, tunnels and critical infrastructures.

This objective was achieved. The test procedure was developed based on available related standards and guidelines. The test procedure describes the conditions for the test specimens, conditioning, test set-up, time-temperature curves, and failure criteria, for transportation bridges and tunnels and critical buildings.

Objective 2: Demonstrate the applicability of the test procedure using an extreme fire test.

This objective was also achieved. A test condition for extreme fire testing of bridge or building column element was simulated using the NRC furnace facility. A calibration specimen was built for the purpose of this test. It was demonstrated successfully that the required time-temperature curve and heat flux for bridges and buildings could be produced using the furnace, based on the specifications in developed testing procedure.

- Technology Readiness Level of Deliverable (TRL)

A TRL of 7 could be assigned from the outcome of this project. The testing procedure was demonstrated in a real extreme fire. The developed test procedure provided a practical method for vulnerability assessment of critical Infrastructures to extreme fires.

- Advantages Over Existing/Competing Technologies

Most of the available test standards are applicable for test of refinery and chemical structures and to some extent to tunnels in extreme fires. There is no extreme fire test guideline for bridges or critical buildings. The new testing procedure not only provides testing instructions for bridges and critical buildings to extreme fire but also provides an equivalent solution for test of unprotected tunnel linings when achieving RWS curve might become a challenge using a testing facility.

Schedule Performance Summary: No time delay was experienced for this project. All tasks were completed as planned in the schedule.

Cost Performance Summary:

The budget for this project was managed according to the initial cost estimate and budget plan.

Annex H Publications, Presentations, Patents

This project includes the following productions:

- The present research report
- Two presentations were delivered to the advisory board members
- A conference paper will be produced and presented

List of symbols/abbreviations/acronyms/initialisms

AB	Advisory Board
CI	Critical Infrastructure
DRDC	Defence Research & Development Canada
NFPA	National Fire Protection Association
NRC	National Research Council Canada
R&D	Research & Development